

United States Air Force Scientific Advisory Board



Report on System-of-Systems Engineering for Air Force Capability Development

Executive Summary and Annotated Brief

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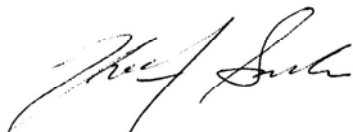
Foreword

Over the past several years, it has become increasingly apparent that although the United States Air Force (USAF) *buys* systems in isolation, it does not *use* systems in isolation. An ever-changing mix of systems, which enable their warfighting capabilities, supports the missions of the Air Force. In an ideal world, the Air Force would build each system involved to satisfy specific and well-understood requirements. Then, each system would fit into its pre-established USAF role supporting whatever capability military leaders called upon for action. The reality is that the Air Force does not build all systems through a homogenous acquisition and development process, it does not use all systems in ways foretold at their inception, and not all systems find themselves used among predicted interface partners. Especially in wartime, the exigencies of war sometimes force a reconfiguration among systems or even demand systems behave in ways that create new capabilities. When such changes occur, the users in the field oftentimes find the tasks associated with reengineering interconnections among systems falls upon them. Increasingly, awareness of the need to support fungible interconnection among systems has driven the Air Force and systems engineers to start thinking about the demands of system-of-systems configurations and the engineering issues associated with building and supporting them.

The *System-of-Systems Engineering for Air Force Capability Development* study was chartered to address the challenge of developing systems-of-systems that are more effective. The study panel conducted this study in response to a request by the Secretary of the Air Force and the Chief of Staff of the Air Force.

In response to their direction, the System-of-Systems Engineering (SoSE) study team received a set of briefings from defense industry organizations, Air Force operating commands, other Department of Defense (DoD) Agencies and organizations, and various universities conducting research related to SoSE. The study team reviewed numerous briefings and other documents from Air Force and Joint organizations concerning system-of-systems operations, acquisition, and development procedures. The assistance of these organizations was essential to the completion of our effort. Their involvement guided the study team toward the findings, concepts, conclusions, and recommendations that comprise this study. The study team greatly appreciates the cooperation of these organizations, and acknowledges the valuable contributions their efforts made to this study.

The undersigned also wish to acknowledge the outstanding effort put forth by the Air Force Scientific Advisory Board Secretariat, the members of the System-of-Systems Engineering study team, the Study Executive Officers, and the Technical Writers in the preparation of this study – whatever value is found in this work is attributable to them.



Mr. Thomas "Skip" Saunders
System-of-Systems Engineering Study Chairman

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Executive Summary

Introduction

Over the past five or six decades, the discipline known as “Systems Engineering” has evolved. At one time, many years ago, development of a capability was relatively simple to orchestrate. The design and development of parts, engineering calculations, assembly, and testing was conducted by a small number of people. Those days are long gone. Teams of people, sometimes numbering in the thousands are involved in the development of systems; and, what was previously only a development practice has evolved to become a science and engineering discipline.

Today, engineers and developers have fairly well codified the processes and techniques for building large, complex systems, and when executed properly, result in reliable and useful systems that serve users well. The challenges of today involve connecting systems, some of which are rather complex systems, together into system-of-systems configurations. This activity has not yet matured to the point of declaring it a discipline; in fact, it is only in the most rudimentary phases of becoming a practice. Consequently, while systems-of-systems are all around us, a theory of engineering applicable to systems-of-systems has yet to be developed.

The Situation

For commercial enterprise, there have emerged many examples of systems-of-systems. Companies can oftentimes serve their business interests when they can form various formal and informal alliances. Some of the time, these alliances are manifest as protocols that can be used to link systems to other systems. One example is the emergence of common usage for certain interconnection standards. For this form of standard, we have chosen a catch phrase “convergence protocol” to characterize the fact that people have chosen a single protocol or standard that simplifies connection among different systems. For example, Transmission Control Protocol/Internet Protocol (TCP/IP) provides a commonly accepted convergence protocol for communication among applications on the worldwide web. These convergence protocols are observable within the commercial enterprise world in many forms and for servicing many different customers. Availability of these convergence protocols has made it much easier for organizations to generate systems that they can connect to other systems and has thereby made it easier to access a much broader market than would be available if they only used private or individual custom protocols.

Some of the existing protocols are electronic, some are information system centric, and some are physical. Consider the common electrical outlet plug, or the widespread use of S-video connections among entertainment products. Yet another example is the emergence of common packaging standards that facilitate freight transport in containers that the airline, rail, sea, and trucking transportation systems can easily move. There are commercial forces derived from business association, profit motive, and market access, which provoke the evolution of convergence protocols.

Adherence to standard protocols allows systems such as televisions to interface to other devices such as digital video cameras, computers, and so forth such that a capability, which

transcends what any one could do on its own, becomes available to the users of the three component systems. It is noteworthy (and an important distinction for what constitutes system-of-systems versus merely a complex system) to consider that a television is a system in its own right. It serves in isolation a useful function to many, and it can be developed as a stand-alone product. Similarly, both video cameras and computers serve useful functions for their owners, and can operate in isolation from the other components of a system-of-systems.

For the U.S. Air Force, the challenges of building a system-of-systems are particularly important because many of the systems already developed can function as contributors to the performance of other systems. However, smooth and simple assembly of a system-of-systems is quite difficult for the DoD. We can trace much of this difficulty to the absence of militarily useful convergence protocols. Where civil/commercially generated convergence protocols are available, the DoD can derive benefit. Nevertheless, even in these cases, the DoD does not always consider the ramifications of ignoring widely used convergence protocols versus adopting unique connectivity among systems. The DoD has habitually emphasized the pre-determination of interconnections among systems, and has therefore designed and implemented connectivity via custom interconnections.

However, the times are changing. The USAF (as well as other parts of the DoD) is now very sensitive to the need for spontaneous interconnection among systems previously thought unrelated. For example, in Desert Storm, information from space sensors was determined to be useful in queuing air and missile defense assets. However, lack of common protocols among those systems forced a long engineering effort to make the relevant systems interoperate.

Increased emphasis on “capabilities” and “effects” has likewise migrated thinking from a platform centric perspective to one that embraces the mutual benefits of having systems work together in synergy to achieve a desired objective capability or even a surprising beneficial emergent behavior.

Findings

As the study began, it quickly became apparent that there was confusion among many people over what constituted a “system-of-systems.” Consequently, study panel devoted some effort towards establishing a common vernacular and a framework for discussing the issues surrounding engineering a system-of-systems. Secondly, it also was quickly apparent that the forces that create system-of-systems alliances in the commercial sector are not always applicable within the DoD. The profit motive does not apply; moreover, there are specific contravening directives against any program manager who would consider incorporating features that might contain speculative benefits. (In contrast, speculatively including capabilities in a commercial system is an often times well rewarded market share enhancement strategy.)

Further, investigation of the state of maturity for engineering a system-of-systems revealed that there was little in terms of codified practice or discipline that could be adapted for use within the DoD. Although there are many examples in the commercial world, and a few examples within DoD, a common development approach is not apparent.

Discussion

Definitions establish a common vernacular and allow discussion to proceed with common understanding among the participants. For the purposes of this study:

A System-of-Systems (SoS) is defined as: *A configuration of systems in which component systems can be added/removed during use; each provides useful services in its own right; and each is managed for those services. Yet, together they exhibit a synergistic, transcendent capability.*

Systems Engineering (SE) is defined as: *The process by which a customer's needs are satisfied through the conceptualization, design, modeling, testing, implementation, and operation of a working system.*

System-of-Systems Engineering (SoSE) is defined as: *The process of planning, analyzing, organizing, and integrating the capabilities of a mix of existing and new systems into a system-of-systems capability that is greater than the sum of the capabilities of the constituent parts. This process emphasizes the process of discovering, developing, and implementing standards that promote interoperability among systems developed via different sponsorship, management, and primary acquisition processes.*

It is assumed that each component system has been well-engineered using traditional Systems Engineering methodologies as a precursor to the formation of a system-of-systems. One important aspect of “goodness” for the application of traditional Systems Engineering is that the perspectives of seven critical stakeholders (i.e., user, acquirer, developer, tester, trainer, sustainer, and researcher) are considered throughout that process. These seven, essentially peer, stakeholders are not always included in processes that purport to modify, improve, or otherwise streamline the acquisition/development processes of the DoD. This can be a serious omission. It often results in shortened or ineffective life cycles for products that take shortcuts. As will become apparent, we propose provision for incorporating these stakeholder perspectives as part of the methodology for System-of-Systems Engineering. This will be accomplished by embedding the stakeholder perspectives in the fielding steps for systems that participate in the proposed methodology.

The new methodology emphasizes four considerations: the human role, discovery and application of convergence protocols, motivation issues, and experimentation venues.

The Role of the Human in a System-of-Systems

Whenever the Air Force generates a system-of-systems, interaction among the systems often includes human-to-human interactions. If the machine-to-machine aspect of SoS is weak, then it falls upon the humans to achieve the interaction. This can, and often does, create a very challenging environment for the human; sometimes leading to missed opportunities or serious mistakes. The lack of sound Human System Interface designs can exacerbate this. Coordinated situation awareness is difficult to manage if the individual systems miss or convey confusing or conflicting information to their operators.

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Assuming there are sound human systems interfaces for individual systems, the Air Force can greatly reduce the burden on the human-to-human coordination if effective inter-system interoperation is established. It is the objective of our study to suggest ways for improving inter-system interoperation at the hardware and software level while keeping in mind that sometimes the human-to-human interaction is the appropriate interface. An effective system-of-systems will promote collaborative decision-making and shared situation awareness amongst the human operators. This occurs by addressing the need for common, consistent human-system interfaces.

Discovery and Application of Convergence Protocols

A highly successful convergence protocol for DoD application in a system-of-systems configuration is the use of discovery technologies for information management among its members. One of the key factors dictating the achievement of system-of-systems configurations that support network centric operations is the availability of mechanisms that promote information sharing among systems. Direct system-to-system linkages presuppose that the systems know a priori about each system that might benefit from any other system. Many combat situations have disproved this assumption. Because of this, a key technology that needs focused attention is intelligent agents to discover and better manage information synergies in dynamic systems-of-systems. While there is substantial development of intelligent agents in commercial markets, born of the competition in internet search engines, this effort will not meet the needs of DoD systems-of-systems because of militarily unique requirements for security, commander's intent, and resource prioritization. As a result, the pace of development of this technology for military systems continues to be a limitation for realizing effective systems-of-systems.

Motivation Mechanisms

The motivations within the commercial market do not easily translate into the DoD environment. Whereas those in the commercial market reward innovation and risk taking with financial and market access benefits, those within the DoD environment hold risk aversion and predictability in much higher esteem. The traditional approach for enforcement within the DoD is promulgation of directives, guidance, instructions, and so forth. Oddly enough, there is no shortage of such documents encouraging good interoperability among systems. However, there is insufficient specificity and detail within that guidance for individual program managers to know exactly what the DoD is asking them to do. The guidance expresses the vision of interoperation and coordinated systems-of-systems very well and repeatedly. However, the tangible steps a program manager must accomplish to embed his/her product with readiness to participate in SoS configurations is absent.

There is a further danger. Premature enforcement of standards can do more harm than good. For example, use of the Ada programming language, and specific directives to use products from the Defense Integration Infrastructure - Common Operating Environment (DII-COE) were declared prior to when they could be reliably and practically adopted. Finding that "effective middle ground" via documented guidance, instruction, and directive is nearly impossible (in our study team's estimation). Consequently, we are suggesting an alternative in which the DoD acquisition process, program managers, and other stakeholders can encourage the

adoption of System-of-Systems Engineering practices as a part of the normal “user requirements” management process.

Experimentation

The use of experimentation with three very specific and differing objectives, we believe, can activate the “other” most powerful enforcement approach available to the DoD: “user requirements.” Aside from directives mentioned above, DoD has deeply engrained the satisfaction of user requirements within its bureaucratic construct for acquiring and developing systems. Therefore, we propose a three-pronged approach that, if properly administered, will dovetail with existing laws, regulations, and procedures for building systems that will be SoS enabled.

The first experimentation venue is devoted to disrupting conventional wisdom concepts of operation (CONOPS). While individual systems are fabricated with the objectives of addressing existing or newly considered CONOPS, the need for synergistic behavior all too often “surprises” the user when they are engaged in wartime activities. Repeatedly, only within the “laboratory” of wartime, do users apply innovative thinking forced by activities of an enemy. That innovative thinking then forces users to consider connecting assets in ways that they never tried before, never trained for before, and perhaps never tested or designed before. The consequence is rapid ad hoc lashing together of systems in a situation of extremis that may or may not prove beneficial to the lives of combatants. Our suggestion is to use an experimentation venue (not unlike that which was originally proposed for the Joint Expeditionary Force Experiment or JEFX experimentation process) to explore innovative CONOPS. It is important to note that JEFX is not providing this service today. It has drifted towards a training and demonstration focus that is unable to tolerate the intentionally disruptive experimentation that we suggest as essential to success. Oddly enough, while the peacetime DoD emphasizes training and predictable behavior of its systems, in wartime DoD needs innovation as its most important leadership and execution attribute. Training of innovation skills is precisely what DoD and the Air Force should explore with the kind of experimentation we suggest; yet there is no current venue for accomplishing that training. There are existing assets (such as the Distributed Mission Operations Center, DMOC) that possess simulation facilities and computer modeling capabilities that could allow much experimentation along the lines we suggest without incurring the costs associated with JEFX; yet these assets are not currently being applied in that manner. Modeling and data collection during experimentation can enable analyses over widely varying scenarios and configurations that will reveal the value of inter-operability, not just at the network level, but also at the system-to-system application level. Therefore, “disruptive and innovative CONOPS experimentation” is the first experimentation venue that we believe the Air Force should activate.

The second experimentation venue is a technical one. The Air Force needs to debate the relative merits of candidate convergence protocols in an atmosphere of tangible experience. Preferences for one or another approach can be debated in open forum, but there is no substitute for hands-on experience and evaluation. Only hands-on evaluation can recognize when a protocol is sufficiently mature for incorporation within systems that must have reliable behavior and predictable benefits. Likewise, we must incorporate precaution against premature dissemination of standards. Consequently, the Air Force should devote the second experimentation venue to the distillation of specific protocol standards that program managers

can incorporate within systems under development. These specific protocols should be defined and characterized in sufficient detail to achieve convergence protocol behavior, but should not be defined as specific vendor products. It is not appropriate to specify specific vendor products, but rather much more effective to specify specific protocol algorithms. The Joint Photographic Experts Group (JPEG) standard for pictorial imagery is an excellent example of the kind of specificity imagined. The decoding algorithm is the expression of this standard. An encoded artifact is JPEG compliant if the well-codified JPEG decode algorithm is able to create a picture out of that artifact. The standard is mute with respect to the encoding algorithm. Thus, there is plenty of leeway for competitors to derive efficient, fast, and high compression, or specially tailored algorithms and to compete among one another for market superiority. Yet the standard has universal application since regardless of the (even proprietary in some instances) JPEG compression applied, the decode algorithm works successfully. Therefore, we believe “convergence-protocol-evaluation” experimentation is the second experimentation venue the Air Force should activate.

The third experimentation venue is one focused on rapid fielding of SoS enabled systems. More than one legitimate path may be followed for the generation of systems that serve the needs of the USAF. Some of these are specifically established as means for streamlined systems development, and some are specifically established to allow user communities to maintain flexibility and responsiveness to emerging immature needs. These alternative acquisition approaches commonly do not take into account the full life cycle of a product; consequently, systems brought to the field with these alternative approaches seldom have long lives. Were there an effective and supportive set of advisors available to these development teams, the leveraging implied by incorporation of the seven critical stakeholders mentioned earlier, could make these “alternative source” products far more effective. From the SoS perspective, it would allow some of the “convergence protocols” derived in the second experimentation venue to be incorporated from the outset in these streamlined acquisition products. Synergy among disciplined practitioners of the seven stakeholders with the speed to field objectives of the system developers could prove beneficial to all parties. There are many details to be worked out here, but the affected participants have people who are creative and innovative within their organizations. We have confidence that under the proper leadership an effective solution providing mutual benefit would enable SoS options for the USAF.

State of SoS Engineering Practice

Lastly, the study panel held numerous discussions with others about the maturity of SoSE. There are schools beginning to establish curricula devoted to the science of SoSE. These schools are investigating mechanisms that underlie SoS opportunities. For example, what are the metrics that the Air Force can apply to systems for evaluating the benefits of incorporating provisions for reconfiguration, flexibility, inter-operability, and so forth that affect SoSE? Of relevance to these programs, the Air Force needs a body of investigation and research for discovering and developing convergence protocols. At a more general level, a theoretic foundation for a predictive analytic SoSE discipline is needed.

Recommendations

We have four recommendations that fall into two categories:

The first category is that of technology exploration. Here, we should 1) establish the experimentation venues as a means for achieving pragmatic near-term results. As described above, these venues should support disruptive, innovative CONOPS experiments, convergence protocol evaluation and selection, and support for rapid provisional fielding of SoS enabled systems. Also from a pragmatic approach, technology that provides discovery among systems and makes association of information needs among the publishers and subscribers is necessary to achieve the full potential of network centric operations. Therefore, we should 2) pursue these enabling technologies.

The second category is that of infrastructure enhancement. Here, we recommend that 3) the USAF task the Air Force research establishment to promote investigation within this topic. There are aspects of such investigation that would be applicable to both commercial and DoD environments, but there are some aspects of such investigation that must be focused on DoD (and USAF) unique constraints. The differences in enterprise environments between commercial interests and DoD legal constraints can have a profound effect upon the direction of research. Only DoD-sponsored research is likely to produce results that are usable within the DoD. To facilitate this properly, we need the involvement of the seven critical stakeholders. Therefore, we also recommend: 4) creation of an infrastructure that would allow full two-way participation of the seven critical stakeholders. The goal here is not only to facilitate their participation in SoS development, but also to provide the opportunity for them to incorporate the new SoSE methodology into their respective bureaucracies.

Summary

The SAB study into System-of-Systems Engineering has developed a set of recommendations devoted to a pragmatic approach to the issues of building component systems capable of assembly as a system-of-systems. We will not fix the problem of “lack of a defined, developed, and applied” SoS Engineering discipline via one report. However, we believe adoption of the recommendations: institution of the experimentation venue, adoption of management strategies that translate SoS convergence protocols into user requirements, and sponsorship of additional research and development (R&D) will help the Air Force move in a healthy direction as well as act as a first step towards building a SoSE discipline. The theoretic perspective for SoSE has not yet been established, but there are several capable R&D organizations standing ready within the academic community and elsewhere. These organizations should be encouraged to pursue further study into this topic.

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Annotated Brief



Air Force Scientific Advisory Board

System-of-Systems Engineering for Air Force Capability Development

**2005 "Quick Look" Study
SAB Summer Session
30 June 2005**

Mr. Thomas "Skip" Saunders, Study Chair

SoS Study Charter



- **Propose a Systems Engineering Methodology**
 - Tailored for AF use
 - Suitable for Software Intensive Systems that include humans as part of system
 - For Robust and adaptable SoS that:
 - Provides validated “useful” operational capabilities
 - Can be delivered at a cycle time matching operational tempo needs
- **Leverage**
 - Existing SE principles
 - Existing “non-traditional” practices
 - Operator expectations of SE
 - Evolving research in SoS engineering
- **Find an exemplar program**

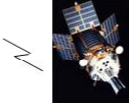
This study was chartered to examine the state of Systems Engineering practice for developing a system-of-systems. We were asked to propose a methodology that the USAF could apply when assembling software intensive systems into configurations that offered useful operational capabilities, and to do so at a pace that would be responsive to operational needs. We were asked to take advantage of lessons from any quarter to include both traditional and innovative practices. Lastly, we were asked to see if we could find an exemplar program that might benefit from our proposed new methodology.

Problem Statement



- Most systems are acquired individually
 - Yet, capabilities are achieved with assemblies of multiple systems
- The unanticipated need for system to system interactions too often require clever, ad hoc work-arounds
- Although weak “systems engineering” is sometimes blamed for disconnects experienced in the field...the real problem:

A SoS Engineering discipline has never been defined, developed, or applied



- Battlefield Consequences:
 - Can't take full advantage of assets
 - Capabilities are “Late to Need”
 - Unanticipated CONOPS “work-arounds” developed on the fly
 - User has to compensate for weak interoperability designs

The Air Force acquires most of its systems individually, to serve the needs of a specific user for a specific purpose. Yet, mission capabilities are usually the result of contributions from multiple users using multiple systems. Sometimes, new capabilities sought would be possible if existing systems were to work together. However, since the Air Force may not have known a priori that it would use the systems in the service of the novel capability, these systems require creative work-arounds to be able to exchange information and work together.

It is not “weak Systems Engineering” at fault; rather, it is the absence of System-of-Systems Engineering. None exists.

Experiences on the battlefield have revealed this problem for many years. For example, in Desert Storm, information from space sensors was determined to be useful in queuing air and missile defense assets. However, lack of common protocols among those systems forced a long engineering effort to make the relevant systems interoperate. More recently, the concept of operations for using the Global Hawk shifted dramatically once its value in theater was recognized. The user, all too often, becomes the de facto systems engineer, acquirer, developer, tester, and sustainer for capabilities such as imagery in the cockpit.

So, Why System-of-Systems Now?



- There is a clear trend:
 - Away from a platform centric view of systems
 - Towards capabilities and effects
- Capabilities and effects are based on collections of systems working synergistically
 - Some systems support multiple capabilities
- We need systems built in ways that facilitate cooperation... in ways that make them capable of operating as a

System-of-Systems

Why has this topic surfaced now? We can trace part of the interest to the notion of Transformation, especially transformation's emphasis on capabilities. Capabilities are usually dependent upon a mix of systems.

However, there is no "one-for-one mapping" among systems and the capabilities they provide. In other words, just as some capabilities depend on multiple systems, some systems support multiple capabilities. The solution of placing one person "in charge" of a capability runs the risk that some systems would fall under the auspices of multiple "in charge" capability managers. So, there is an expectation (or at least a hope) that some form of Systems Engineering practice encompassing both system development and system-of-systems development levels will facilitate the synergistic assembly of systems into something that achieves useful, operationally relevant capabilities. We conducted this study to examine these possibilities.

Bottom Line Up Front (BLUF)



- A “System-of-Systems” is different from a “System”
- SoS Engineering
 - involves managing future uncertainty
 - not a well codified discipline (yet), it is a practice
 - Commercial world motivations do not translate easily to DoD world
 - depends on:
 - Well engineered systems PLUS
 - New processes to define and leverage user requirements such that systems are SoS enabled
- Recommendations
 - Establish *three experiment venues*
 - Build *technologies* that support convergence protocols interoperation
 - Promote research into discipline and theory of SoSE
 - Institute management approaches that motivate *7 critical systems engineering stakeholders* to embrace SoS solutions

As has become a tradition for SAB studies, we disclose the punch line up front. In the case of this study, the punch line is “experimentation.” Although SoS engineering has not matured enough to be a true discipline, practices have appeared that seem to nurture system-of-systems development. Those practices are a combination of well-practiced traditional Systems Engineering, plus the emergence of certain technical products and architectural styles prevalent in information systems. What we are seeking is some means of accelerating what seems to happen naturally, but at too slow a pace. We have become convinced that the Air Force could influence (accelerate) the pace of system maturity and evolution of important systems attributes via judicious use of experimentation.

We also capitalize on some of the recommendations from our “sister study” “Domain Integration” chaired by Dr Pete Worch and Professor Alex Levis. Most notably, our study ratifies their suggestion that certain service oriented architecture constructs are beneficial for achieving domain interoperation. Such constructs are also important for the rapid assembly of a system-of-systems.

We also point out that System-of-Systems Engineering depends upon motivating and engaging the critical stakeholders in traditional Systems Engineering processes. We do not discard traditional Systems Engineering in favor of a new methodology; rather, it needs to be augmented to support development of a system-of-systems.

Therefore, our recommendations are the establishment of three new experimentation venues for the USAF to achieve critical insight into the benefits and challenges of a system-of-systems. It is difficult to motivate engagement in a concept unless the benefits are readily apparent to the proposed beneficiaries. That is a long-winded way of saying “You can lead a horse to water, but can’t make it drink.” Users will not embrace system-of-systems solutions if

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they do not perform a useful capability. Moreover, and perhaps most important, the benefits of complying with a system-of-systems architecture will not be apparent if the flexibility achieved with that architecture are not understood. The foundational support for including system-of-systems enabling requirements within individual systems will not happen unless such flexibility is valued. We therefore suggest that an experimentation venue that forces users to consider innovative CONOPS will be an important part of developing healthy systems-of-systems. The JEFX experimentation venue might appropriately be changed to perform as this venue. Operationally oriented experiments will help users learn how to respond to threat environments with flexible application of existing systems. Next, the technical and systems engineering community needs a second experimentation venue to define and gain practical technical experience with what we might call “market enabling convergence protocols.” This is the “technical Aha!” part of the USAF SAB investigation, and mostly described by the “Domain Integration” study report. Lastly, we propose an experimentation venue for the acquisition community that they can use in a practical sense to accelerate the movement of new systems capabilities to the field. We will introduce the notion of “provisional fielding” as a means for sponsoring both improved traditional Systems Engineering discipline for the systems we currently develop as stovepipe development efforts as well as for including some of the loose couplers described in the “Domain Integration” study among all systems which may become candidate components within a system-of-systems configuration. We recommend Air Combat command and the Deputy Chief of Staff of the Air Force for Plans and Operations (AF/XO) pursue the CONOPS experimentation venue. The Air Force Research Lab, the Assistant Secretary of the Air Force for Acquisition (SAF/AQ), and Secretary of the Air Force, Office of Warfighting Integration and Chief Information Officer (SAF/XC) should work together to pursue infrastructure experimentation. SAF/AQ should also pursue experimentation for provisional fielding.

The second recommendation is for the development of some specific technical capabilities that allow systems to discover the presence of other systems relevant to their mission. Too often, information is available in “the enterprise” that does not reach all the potential beneficiaries. For example, agent technology that provides performance advocated by the 2000 SAB study on the Joint Battlespace Infosphere (JBI) (Ref: SAB-TR-99-02) needs accelerated development. There is also a need for investment in modeling tools to support the kind of disruptive-innovative concept of operation experimentation we advocate. In particular, understanding network behavior in an environment of system-of-systems operation would be useful to investigate. We recommend responsibility for this go to the Commander, Air Force Research Laboratory (AFRL/CC).

The third recommendation is for the development of a much more disciplined approach to understanding the engineering issues surrounding systems-of-systems. This study concentrated on pragmatic steps the USAF might follow for improving its experiences, but there is a need for a more theoretic investigation that would result in the ability to conduct predictive analysis and behavior estimates for an emerging SoSE discipline. We believe responsibility for this should go to the Air Force Office of Scientific Research (AFOSR).

The last recommendation is for the pursuit of management approaches that engage the critical seven stakeholders in any Systems Engineering methodology. Motivational forces are needed within each to participate in successful pursuit of SoSE. So, building alliances among the different organizations and cultures affected by SoSE would likely contribute strongly to

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improved outcomes for system-of-systems. We recommend that SAF/XC should take responsibility for forming the IPT. Further, we recommend that IPT membership should include the following:

Air Combat Command (ACC)

Air Force Space Command (AFSPC)

Assistant Secretary of the Air Force for Acquisition (SAF/AQ)

Air Force Operational Test and Evaluation Center (AFOTEC)

Air Education and Training Command (AETC)

Air Force Materiel Command (AFMC)

Air Force Research Laboratory (AFRL)

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Mr Justin Waters	Technical Assistant

The study panel was comprised of a set of people with diverse backgrounds and experience, but each of who brought perspectives important to our investigation of this rather complex subject. Having people with such outstanding, Government, military, industrial, and academia backgrounds and credentials helped maintain focus on what we hope are useful and innovative recommendations for the USAF.

Visits, Briefings and Discussions



Department of Defense

Missile Defense Agency
OSD-AT&L
OSD-NII
OSD/PA&E/RA/CAIG

Department of Homeland Security

US Coast Guard

Headquarters Air Force

SAF/AQRE

Functional MAJCOMs

Air Combat Command Headquarters
AFC2ISRC
ESC-CC
ESC-EN

FFRDCs

The Aerospace Corporation
MITRE

Industry

Boeing Integration Center – East
Boeing Integration Center – West
Concurrent Technologies Corporation
Lockheed Martin Center for Innovation
Northrop Grumman Cyber Warfare
Integration Network

Universities

California Institute of Technology
George Mason University
Massachusetts Institute of Technology
Old Dominion University
Purdue University
Stevens Institute of Technology
University of California San Diego
University of Southern California
University of Virginia


We went to many places and discovered that a large number of people and organizations are giving considerable thought to the issues and benefits of assembling a system-of-systems. Moreover, there is substantial resource investment taking place that offers potential to leverage support for some of the more “resource intensive” recommendations we make. In general, we were encouraged during our information gathering visits for the prospects of System-of-Systems Engineering.

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1. Definitions



Definitions

- **Experiment (ik-'sper-ə-mənt):**
 - **Something to do when you don't know the outcome**
- **Demonstration (de-mən-'strA-shən):**
 - **Something to do when you want to show a skeptic what you already believe**
- **Requirements (r-'kwlr-məntz):**
 - **What you say when you know what you want**
- **Systems ('sis-təmz):**
 - **What systems engineers build to satisfy requirements**
- **Surprise synergy (sə(r)-'prlz si-nər-jE):**
 - **What you get when you knew you wanted something good, but didn't know how to ask for it**
- **Systems of Systems ('sis-təmz əv 'sis-təmz):**
 - **What SoS engineers build to achieve surprise synergy**

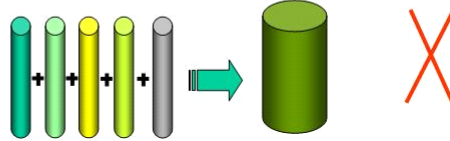
A few definitions are worth considering. First, the distinction between experiment and demonstration is critically important. Misunderstanding of the purpose of an experiment would severely disrupt the ability to execute the recommendations of this study.

Similarly, misunderstanding the ultimate contribution from sound System-of-Systems Engineering would easily allow the Air Force and DoD to misinterpret our recommendations as “activities already underway”. We wish to emphasize that predicted behavior should be the product of sound Systems Engineering. Tolerance for future needs is the objective of sound System-of-Systems Engineering. Achieving “surprise synergy” is the objective whereby users discover systems in the field are interoperable even though developers did not design those specific systems that way at the time of a system’s development.

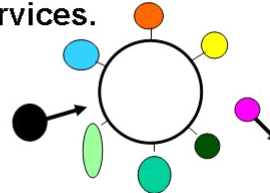
What is a System-of-Systems? Distinguishing Real From “Faux”



- From small stovepipes to large stovepipes – is NOT systems of systems



- Component systems can be added/removed during use; each provides useful services in its own right; and each is managed for those services.
- Yet, together they exhibit a synergistic capability.



Ref: Dr Alexander Levis

Our discussion of System-of-Systems Engineering (SoSE) depends upon clear differentiation of the System-of-Systems (SoS) from the large-scale system. A common misconception is that a transition from small stovepipes to very large stovepipes implies an SoS; this is incorrect. A true SoS is comprised of component systems that users can add or remove during use, with each providing useful services in its own right, and they can manage each for those services. The SoS is created when these are combined in such a way as to deliver a capability, enabled by the *synergy* of the component systems. Such capability cannot be delivered by the simple summation of the standalone capabilities of the SoS's component systems.

It is beneficial to consider Dr Mark Maier's characterization of distinguishing features for an SoS. These attributes become important because of the criteria for applying some of the engineering practices we propose are most appropriate for SoS, and are probably not so relevant to systems that are merely “large and complex.” (For these large and complex systems, traditional Systems Engineering should be sufficient, assuming it is properly applied.)

Maier (1996)¹ highlights five characteristics that distinguish the SoS from very large complex monolithic systems:

1. **Operational Independence of the Elements:** If the SoS is disassembled into its component systems, they are still able to operate independently in a useful manner.
2. **Managerial Independence of the Elements:** Component systems are separately acquired and continue to be managed independently.

¹ Maier, M., “Architecting Principles for Systems-of-Systems”, *Proceeding of the 6th Annual INCOSE Symposium*, p. 567-574, 1996.

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3. **Evolutionary Development:** The SoS evolves over time, with component systems capabilities added, removed, or modified as needs change and experience is gained.
4. **Emergent Behavior:** The SoS has emergent capabilities and properties that do not reside in the component systems.
5. **Geographic Distribution:** The SoS component systems are geographically distributed but have the ability to readily exchange information.

System-of-Systems Engineering Two Perspectives



- A “capability” perspective:
 - System-of-systems engineering is the interdisciplinary, **CROSS-SYSTEMS** process that ensures the development and evolution of **CAPABILITIES** to meet multiple stakeholders’ evolving needs across periods of time that exceed the lifetimes of its individual systems

Ref: Dr. Jeremy Kaplan; 1st Annual conference on SoSE
- A “connecting the parts” perspective:
 - System-of-systems engineering is the process of discovering, developing, and implementing standards that promote interoperability among systems developed via different sponsorship, management, and primary acquisition processes

The set of systems comprising a system-of-systems includes independently capable systems, that when integrated, deliver significantly greater capability. A single system (or less than full combination of all involved systems) cannot provide the capability achieved by the system-of-systems. There are two legitimate perspectives relevant to the engineering of the SoS: (1) the capability oriented perspective and (2) the “connecting the parts” perspective.

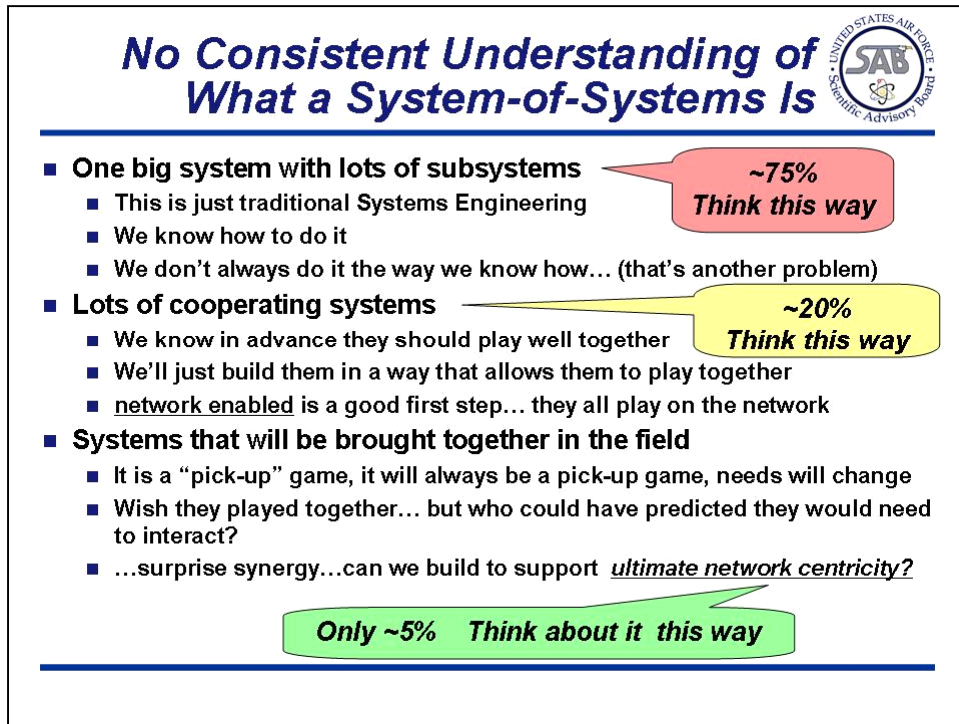
Capability Oriented Perspective: This first perspective relates to the overall process for establishing new capabilities via an SoSE process with continuing evolution over the SoS life cycle as the needs and opportunities for delivering new capabilities arise. Thus, the SoSE process must provide for mechanisms to discover and promote new capabilities and synergies that arise in yet unrealized systems-of-systems while establishing the impact of new CONOPS on the performance, utility, and development of the constituent systems. This perspective also recognizes that the SoSE process must be in harmony with the traditional SE life cycle development processes of the individual component systems endeavors.

“Connecting the Parts” Oriented Perspective: The second perspective recognizes that the SoS is built from a collection of independently acquired and operating systems that must now be connected together. Therefore, there must be specific mechanisms that allow the component systems to come together. Interoperability standards are the primary mechanism to enable effective connection of the parts, enabled by an environment that fosters standardization. It is important to point out that consistent protocol behavior is the property that enables interoperability. Adherence to a specific product is often over-constraining and provokes problems with respect to version upgrades. A carefully crafted definition of the protocol is a better means for a long-lived approach towards establishing interoperability among systems that may be developed during different timeframes, from different sources, and from differing organizations or missions. As a result, an important element of future SoSE implementation will

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be the identification, development, and verification of robust interoperability standards that through testing and time become unassailable "must haves" in each individually procured system.

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Researchers can find multiple definitions of System-of-Systems Engineering in the literature. This study has shown that there are at least three unique views on SoSE, and that few people are thinking about SoSE in a manner that will yield the desired outcomes for Air Force systems.


It is concerning that approximately 75% of subject matter experts consulted in the study viewed an SoS as just a big system with lots of subsystems, with a perspective that it requires only traditional SE. This perspective is “*we know how to do it...we don't always do it the way we know how*” (that is another problem).

About 20% of the subject matter experts consulted in the study offered a more progressive view. These people viewed an SoS as many cooperating systems, where we know in advance that they should play well together. The approach is to build them in a way that allows them to play together with network enabling as the good first step.

Only about 5% had the desirable perspective of SoS as collaborative systems that will be brought together in the field, recognizing it as a “pick-up” game that will always be a pick-up game as needs will change. In this view, the perspective is that the SoS involves many legacy systems that we “wish they played together, but who could have predicted they would need to interact?” In this view, there is “surprise synergy” and the challenge is perhaps to build to support ultimate network centrality.

A shift in mindset will be necessary to move the industry forward to thinking about SoSE as a discipline that builds upon traditional Systems Engineering approaches, but involves new approaches and enablers to evolve and sustain a system-of-systems.

Pre Condition: Systems Engineering is Effectively Applied to the Individual Systems Within the SoS



Systems Engineering is the process by which a customer's needs are satisfied through the conceptualization, design, modeling, testing, implementation, and operation of a working system

- Engages all the contributors to a system's life-cycle
 - **Users** – people in the field who benefit from system
 - **Developers** – people who construct the system
 - **Acquirers** – people who contract for and pay for system
 - **Testers** – people who evaluate system for suitability
 - **Trainers** – people who ensure users know how to use it
 - **Sustainers** – people who keep system up to date
 - **Researchers** – people who provide next generation ideas
- Considers external factors – threat, risks, adversaries, or market competitors which influence the system's ability to support customer needs

Seven (+1) Critical Stakeholders

Systems Engineering is the process by which a customer's needs are satisfied through the conceptualization, design, modeling, testing, implementation, and operation of a working system. It is a full life cycle discipline. It engages all contributors in the system's life cycle including users, developers, acquirers, testers, trainers, sustainers, and researchers. In any Systems Engineering methodology, it is important to consider the perspectives of each of these stakeholder communities. Too often, what appear to be good, new methodologies (e.g., Pre-Planned Product Improvement, Evolutionary Acquisition, Spiral Acquisition, and so forth) run into difficulties because balance among these seven stakeholders is not included. This is not necessarily the fault of the new methodology concept; it is more often the fault of the implementation. If the SoSE methodology proposed here is to be successful, its implementation needs to have participation from each of these stakeholders.

In addition, good Systems Engineering also considers external factors including threats, risks, adversaries, or market competitors influencing the system's ability to support stakeholder needs.

Many standards and guidebooks today describe the Systems Engineering process and practices. In addition, recent studies of Systems Engineering in the defense industry have concluded that its practices are sound, although not always effectively applied. SE Revitalization policies² issued by the DoD and Air Force target the unresolved issues of insufficient attention to and application of Systems Engineering in programs.


The Systems Engineering process is applied to the development of complex systems, as well as to development of the subsystems that comprise it. A full life cycle process invokes the

² SE Revitalization policies and recent guidance can be found on the Air Force Center for Systems Engineering website: <http://cse.afit.edu>

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contributions of the multi-disciplinary team at appropriate points in the life cycle and includes milestone reviews. In an SoS, this traditional Systems Engineering process continues to be applied to the component systems comprising the SoS but it is not sufficient in itself for SoSE.

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What Differentiates Engineering of a System Vice a System-of-Systems? 		
	Traditional Systems Engineering	System-of-Systems Engineering
Purpose	Development of single system to meet stakeholder requirements and defined performance	Evolving new system-of-systems capability by leveraging synergies of legacy systems
System Architecture	System architecture established early in lifecycle and remains relatively stable	Dynamic reconfiguration of architecture as needs change; use of service oriented architecture approach as enabler
System Interoperability	Defines and implements specific interface requirements to integrate components in system	Component systems can operate independently of SoS in a useful manner. Protocols and standards essential to enable interoperable systems
System "ilities"	Reliability, Maintainability, Availability are typical ilities	Added "ilities" such as Flexibility, Adaptability, Composeability
Acquisition and Management	Centralized acquisition and management of the system	Component systems separately acquired and continue to be managed as independent systems
Anticipation of Needs	Concept phase activity to determine system needs	Intense concept phase analysis followed by continuous anticipation, aided by ongoing experimentation

In 1961, Simon Ramo, addressed the First Systems Symposium at Case Institute of Technology. In that address, he remarked that the outcome of the race between Systems Engineering versus the rapidly increasing complexity of our growing civilization would be "determined, in effect, by whether Systems Engineering as a discipline is able to grow and develop quickly enough to successfully meet the problems of our future."³ While Systems Engineering has continued to evolve and mature, we face the same challenge for a discipline that can address complex SoS problems. A successful outcome will be the development of an SoSE discipline that will complement but not replace the traditional SE practices. Traditional SE remains essential to development of the individual product systems and subsystems, the building blocks from which a system-of-systems is created. The table above compares some of the facets of traditional SE to SoSE.

In contrast to the engineering of a single system, the discipline of SoSE must accommodate larger scope and greater complexity of integration efforts, collaborative engineering processes in an extended enterprise, and engineering under conditions of high uncertainty. Decision-making may involve difficult decisions such as a delay of individual legacy system upgrades to respond to urgent needs to deliver capability or improved performance in the overall SoS. Architecture becomes critically important with the SoS requiring the ability to reconfigure the architecture dynamically to respond to changing needs and threats, as well as to the availability of new system technologies. Understanding and responding to emergent SoS behavior – both positive and negative – is another important aspect of SoSE. To address such challenges, traditional Systems Engineering is necessary but not sufficient for the engineering of a system-of-systems.

³ Ramo, S., forward to Systems: Research and Design, Proceedings of the First Systems Symposium at Case Institute of Technology, ed. Donald P., Eckman (New York, 1961)

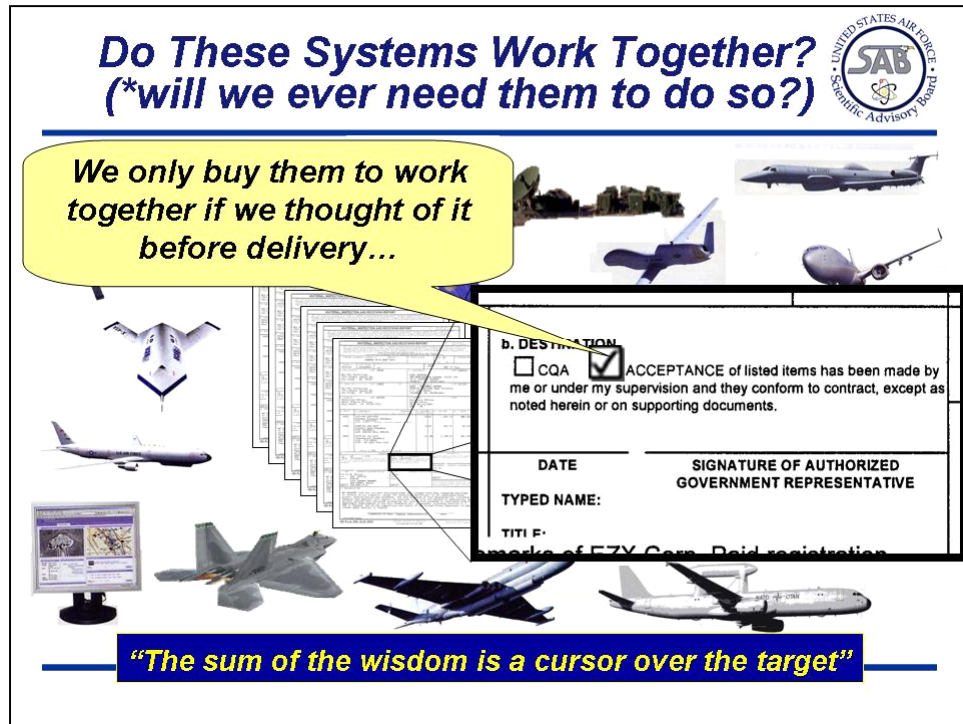
Comparing traditional SE and SoSE from the perspectives of seven key stakeholder groups enables further understanding of changes in approach and methods for SoSE, as shown in the table below.

<i>Table 1. Comparison of Stakeholder Perspectives for Traditional SE versus SoSE</i>		
	<i>Traditional Systems Engineering</i>	<i>System-of-Systems Engineering</i>
User	Defined set of people in the field who benefit from system with relatively well understood expectations.	Changing set of people in the field who benefit from evolving system-of-systems in response to dynamic needs.
Developer	System developed by prime contractor and subcontractors with single program office. High degree of focus on the integration of the system components to specified level of performance.	Development is distributed with collaboration of multiple contractors and suppliers, responding to multiple program offices. Component systems may be in varied life cycle phases. Effective human systems integration is critical.
Trainer	Trainers with high degree of knowledge of system deliver training based on system intended use; training changes incrementally when system upgrades are delivered.	Trainers need to understand highly complex and evolving SoS; training will need to be personalized based on dynamic needs of sets of stakeholders at needed point in time.
Tester	Verification and validation in accordance with V-model of system to well specified set of requirements and documented needs; master test plan drives testing activities.	Will involve increased use of models and simulations and use of experiments to formulate validation approach. Requires high degree of coordination of cross system testing activities.
Sustainer	Sustainment needs and requirements planned in front end of systems effort; sustainment activities performed by single organization.	Sustainment needs and requirements will evolve as SoS evolves; high degree of coordination across multiple sustainment organizations is required.
Acquirer	Sound acquisition practices used to select and manage prime system contractor. Direct relationship between acquisition and contractor program offices.	Complex planning and negotiations will be necessary for SoS, as well as coordinated acquisition of component system capabilities. Some centralization of SoSE management via use of a Lead Systems Integrator role.
Researcher	SE research efforts are typically program focused; performed in program laboratory involving modeling and simulation; and research is performed in early phases of system development or directed at specific system enhancements in later phases. Research is directed at program/domain specific problems.	Cross program focus demands collaborative approach and shared research facilities; high degree of experimentation is involved on continuing basis; collaboration of government, industry and academia is essential. Research directed at crosscutting problems involving complex synergies of technologies, socio-technical issues, policy, and enterprise factors.

2. Problem Characterization



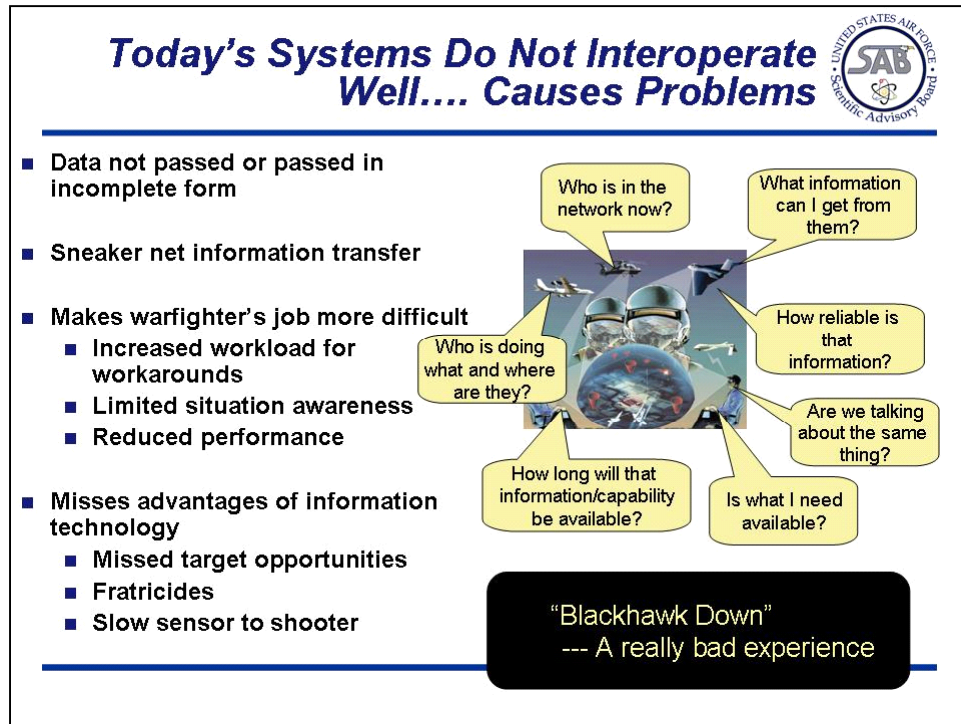
Consider the USAF systems appearing on the chart: Do they work together? What about the Army and Navy systems, can we interoperate with them? What about the systems of other nations, can we interoperate with them as well? (Note that “coalition” is not limited to countries with English as their native language.) The question we must wrestle with is “will we EVER need them to work together? (If so, what could we do about it?)”



For each of the U.S. systems involved, there is something called a DD250. This is the final document in a system’s development process. It is the one where the “Authorized Government Representative” checks the box and signs on the line, accepting the system and permitting payment to the contractor. If a delivered system is going to play with other systems, a developer must consider that inter-play and include it in the requirements for the system. Our traditional Systems Engineering approach has excellent provisions for supporting those “work together” relationships if they are included in the original requirements. However, what do we do about unanticipated CONOPS? In addition, what should we do about unanticipated inter-system relationships?

If the Air Force is to realize the true potential of “Sum of the wisdom is cursor over target,” it needs to build systems in a way that allows them to behave in the most robust of network centric concepts. We need to build them with system-of-systems potential enabled from the beginning. In the absence of having built systems to be system-of-systems configured, we need a means for backfilling systems.

The questions remain. What enabling technology do we need to define? How will we discriminate good technologies? How will we know which component systems we should outfit with system-of-systems enablement?



Today's systems not being developed with a system-of-systems perspective provide only a loosely coupled conglomeration. They either do not pass data at all, or only partially pass data between components. Often the human must manually derive, transform, and reenter information between systems.

As the option of last resort, the human operator can only partially compensate for these shortcomings. In trying to gather and process the needed information, he or she ends up with a significantly increased workload and limited situation awareness. In many cases, they may never discover what they really needed to know.

Sometimes, as experiences from Somalia would indicate, the human becomes overloaded trying to compensate for situation awareness mismatches among supporting systems. There were instances where people were talking to party A, when they thought they were talking to party B. The consequences when Party A executed instructions intended for Party B were disastrous. Likewise, when Party B never got their intended instructions, the outcome was not desirable.

The result of systems-of-systems having poor interoperability is that we are failing to realize the true potential of what all systems working together as a whole can achieve. This results in missed target opportunities, fratricides, and slow sensor to shooter performance. Today's systems do not operate effectively as true systems-of-systems.

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3. *The System-of-Systems Engineering Methodology*

To address these shortcomings of the current state of affairs, the Air Force needs a System-of-Systems Engineering process. We have identified four main factors that require consideration in improving System-of-Systems Engineering in the Air Force:

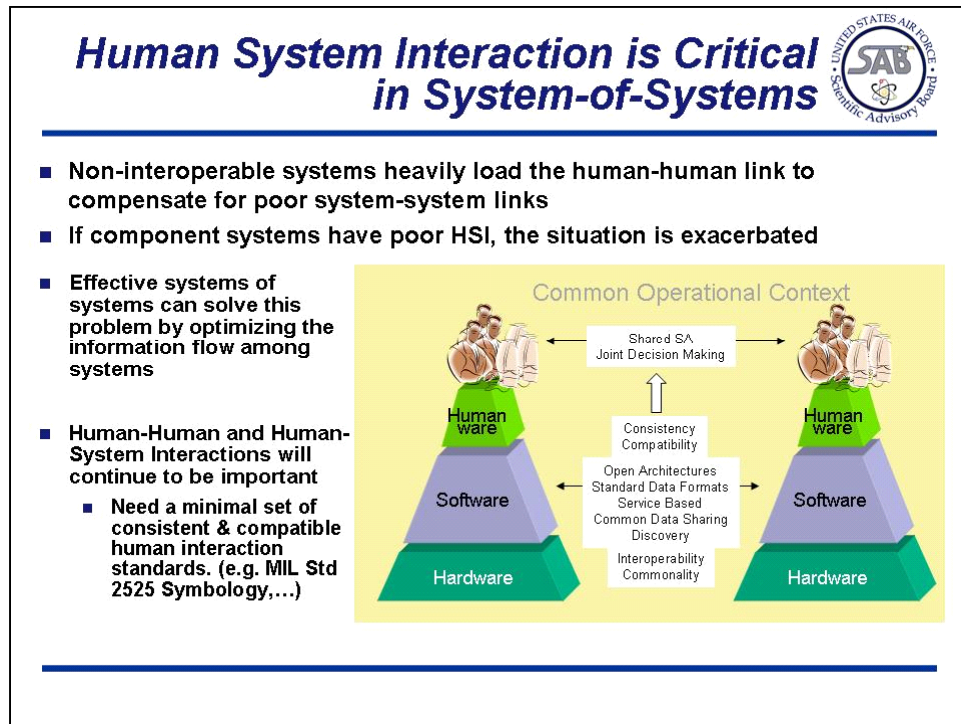
- The first of these is the need to include human system interaction as a part of System-of-Systems Engineering
- The second is the need to identify the convergence protocols that enable the critical loose coupling linkages among system components
- The third is the need to address the key motivators in the system procurement and development process that currently hamper good system-of-systems development
- The last is the need to incorporate discovery learning through experimentation at the system-of-systems level

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3.1. The Human Role

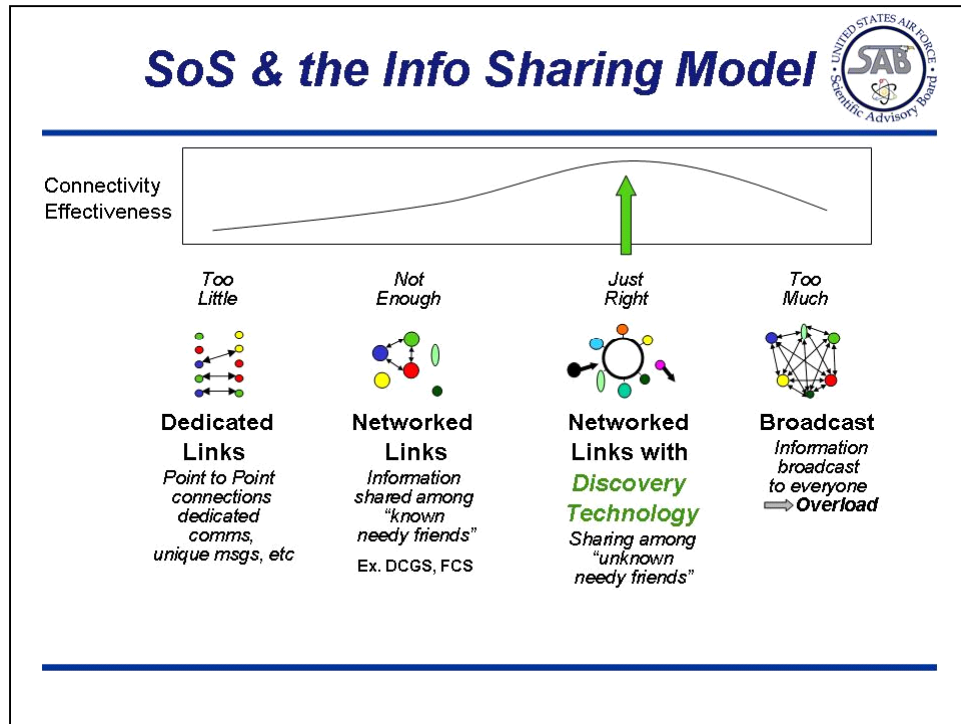


In an effectively performing system-of-systems, mission performance is dependant on effective joint decision-making and collaboration among the components. Achieving this is all about enabling effective and efficient information sharing.

In today's systems, where direct sharing of information between systems is low, the human-to-human link is heavily loaded in shouldering this burden.

Systems-of-systems can address this problem by significantly improving the information flow between the systems components. We acknowledge this network connectivity as a key component of a system-of-systems.

However, we should recognize that human-to-human and human-to-system interactions would continue to be critical components of effective systems-of-systems. Collaborative decision making, for example, requires that human operators share a common picture of what is happening on the shared, relevant aspects of the mission. Just as systems need to be able to interoperate in order for people to interoperate, they also need an established set of commonality and consistency rules in their interface designs. These rules need to be addressed within System-of-Systems Engineering. Regardless of the system-to-system collaboration requirements, the individual systems need to incorporate sound human-to-systems interfaces.

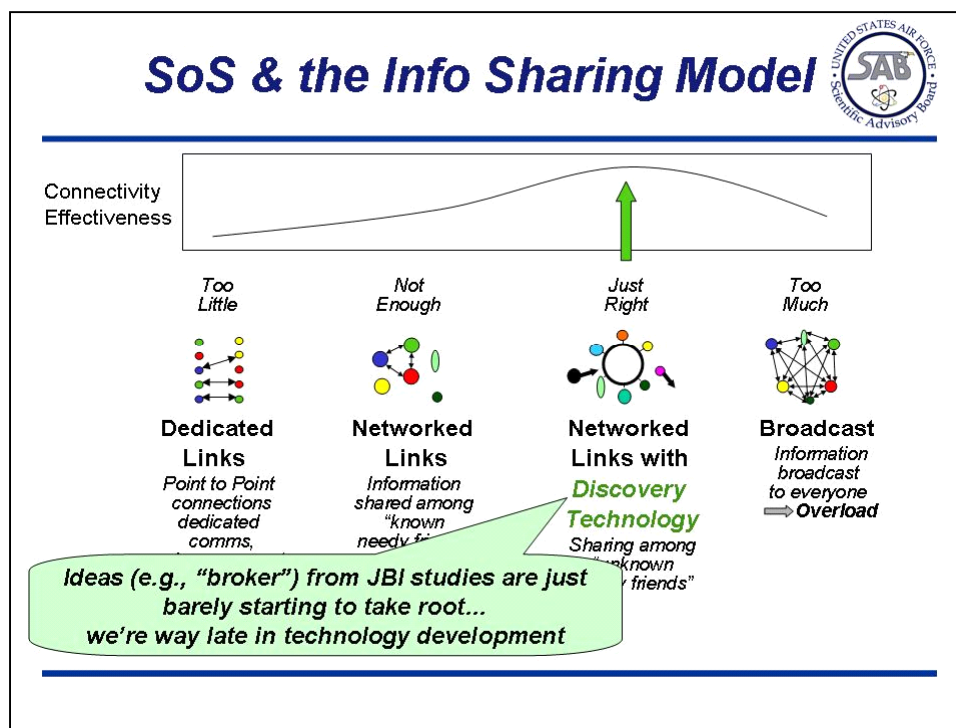


The recognition that the systems supporting warfighters could perform considerably better than they have if users could more easily interconnect them partially drives the emergence of network centric operations. Interoperability among systems is complex. Of course, they need to have communications connectivity. In earlier days, the connectivity among systems was established with unique communications devices. The flexibility was very limited, since only systems equipped with the particular communications mechanisms could pass information among each other.

The emergence of the network allows a simplified communications structure: Presence on the network allows (in principle) information access. In practice, we build systems to allow information exchange via "internet" standards, but unless we establish prior arrangements, the benefits of network enablement are limited to the exchange of bits rather than the exchange of "information." Systems' internal business rules for what information is accessed and how it is processed are still structured upon the presumption that a definition exists for "information exchange requirements" for every information exchange over the network.

One form of connectivity over a network would allow broadcast of information to each recipient system. Not only does this challenge the bandwidth capabilities of communications systems that support the net, but also the resultant information overload can diminish rather than enhance the operator's responses.

A healthy balance between information overload and information exchange among predetermined recipients would be the emergence of "discovery agents" or "brokers" which recognize the opportunity for recipients to receive information that they might otherwise miss.



The notion of a broker is not new. The developers of the Joint Battlespace Infosphere concept built it upon the premise that they could introduce this technology into the network. Sadly, the emergence of this technology is not taking place in military systems. Some commercial development has taken place. This development continues to gain interest in the form of sophisticated search engine techniques. However, these search engines do not have the real-time performance, secure authentication, or commander's intent properties that a discovery agent should show in the DoD network.

There is a need for technical investment into this technology that is critical to the achievement of the network centric operations vision.

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3.2. Convergence Protocols

Systems-of-systems are all around us. Some examples are: The highway system, the various utilities, the internet, the high-level architecture protocol maintained by the Institute of Electrical & Electronic Engineers (IEEE 1516) which allows simulation models to work together, and so forth. Consider the collection of electrical appliances in a house. A complex collection of power plants, hydroelectric dams, solar, and wind driven generators provide electricity. It does not matter which system provides electricity for a particular household appliance. The systems-of-systems that generate electricity all are able to provide that power to a diverse set of appliances in a household through the common “loose coupling” devices known as wall sockets and plugs. Note that a mechanical standard is insufficient to allow these systems to interconnect. One needs to also specify voltage (110, or thereabouts), 60 Hz (and accurately maintained at 60 Hz or the electric clocks will not keep proper time.) The collection of physical and electrical properties comprises a “protocol.”

Protocol is a term used to cover a variety of properties. For information systems, a protocol would characterize not only the physical connector, but it may also refer to the value of voltage, frequency of a signal, pulse widths, and so forth that are used to convey information. The protocol definition may also characterize the sequence of bits (e.g., most significant bit first or most significant bit last in a series of bits). It may include information field definitions so that the system passes different predefined parameters as part of the handshake between two systems using a protocol. In other words, the protocol can be so complex that it serves many information exchange issues that commonly occur between information systems. For non-information systems, protocols can likewise be relatively complicated. For example, in the highway system, the protocol for traffic management includes rules (such as drive on the right, stop for red lights, and so forth) as well as physical properties associated with the width of roadways, permitted weights and heights of vehicles, and so forth.

In all cases, the use of protocols defines certain expected behaviors among the participants in a system-of-systems.

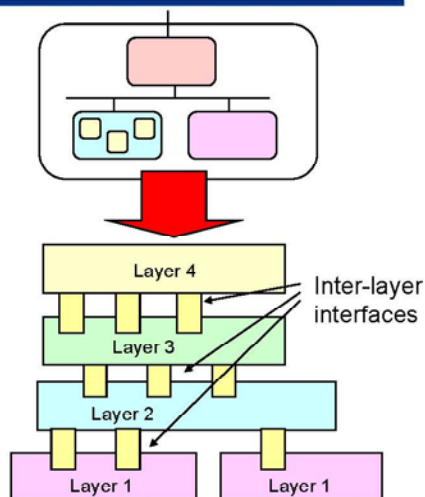
Sometimes, a protocol emerges that, by influence of common acceptance, becomes an enabling protocol for market access. Conformance to the common protocol provides benefits to the users of the protocol because it allows them to leverage the number of other conforming products to improve further their product’s attractiveness among users. It would not be very attractive for a vendor of lights to “invent” a new/better light bulb that has a socket that is different from what is commonly found among lamps. In exceptional cases, vendors may attempt divergence from the standard, but the investment is high, and the penalty for non-acceptance is market rejection. Hence, most purveyors of light bulbs manufacture them to fit in a standard socket and to operate with 120V, 60Hz, AC.

When a community popularly accepts a single protocol, and this protocol allows multiple systems to interact with one another, we call that protocol a “Convergence Protocol,” because the community has converged upon it as a universal standard.

Key Element: Layered Models

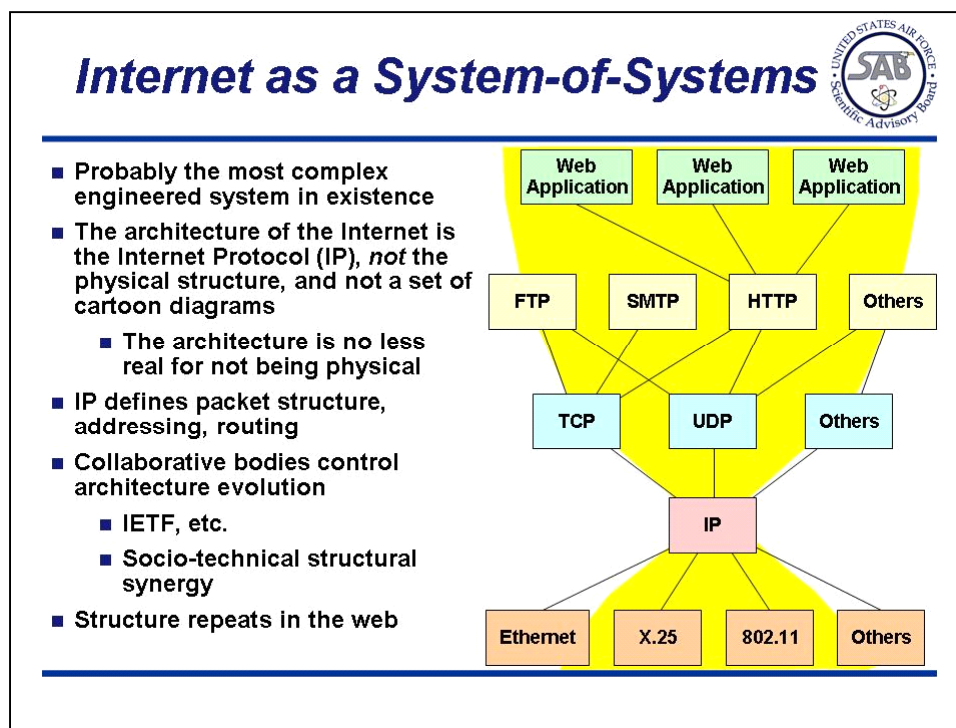


- A hierarchical model of a system describes it in terms of subsystems, components, etc.
 - Interfaces link components. The interfaces might themselves be thought of as components
- An alternative way of viewing a system-of-systems is in *layers* - each layer expresses "services" which upper layers utilize
- A (unanticipated?) by-product of layering has been the adoption of pre-eminent layers (e.g., IP in the case of network protocols).
 - These are layers which become "market-enabling, convergence protocols"



In traditional Systems Engineering, a complex system is broken down into a nested hierarchy of subsystems, with interfaces linking the individual components. This point of view works very well for systems with top-level requirements and a single entity responsible for product development. However, it is difficult to implement this for systems-of-systems, because the requirements are often not known when the individual systems are being designed and they change as the systems (and operational uses of the systems) evolve.

A key approach to System-of-Systems Engineering in the commercial sector, especially in the communications industry, is the use of "layered architectures." In a layered model, the overall system-of-systems is broken down into different collections of services, with each collection expressing the services that are available to layers above it in the "protocol stack." Layered architectures allow different developers to work in parallel and insure that changes in one layer of the protocol do not interfere with operations above and below that layer. Thus, a layered protocol implements loose coupling between the services that makes up the overall system-of-systems.



The prototypical example of a system-of-systems is the Internet, which is perhaps the most complex engineered system in current existence. The Open Systems Integration (OSI) Reference Model specifies the protocol stack for the Internet. This model specifies the services provided at seven layers (i.e., application, presentation, session, transport, network, data link, and physical). Examples of application layer protocols include HyperText Transport Protocol (HTTP) and File Transfer Protocol (FTP). Examples of network protocols include IP (Internet Protocol), NetBIOS Extended User Interface (NetBEUI), and X.25. IP has emerged as a clear standard at the network layer; it defines the structure of a packet of information, including information required for addressing and routing. Indeed, IP has become so ubiquitous it has enabled entire industries by making their products IP compatible.

IP is thus an example of a “convergence protocol.” Convergence protocols enable systems-of-systems by creating the opportunity for rapid and diverse innovation both above and below the convergence protocol. By creating a single standard that everyone can use, developers at lower layers of the protocol can innovate without worrying about the applications that will eventually make use of their components (assuming that they use the convergence protocol). Similarly, developers at higher levels of the protocol stack do not need to concern themselves with the lower level details of the system structure.

Derivation of Convergence Protocols



- What stimulates creation of Convergence Protocols?
- What technology enables us to make them?
- What Systems Engineering build & management processes provide good results?

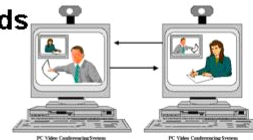
■ Type A - Monopolies

- Single entity controls all decisions (and \$\$)
- Example: RJ11 phone jacks
 - Dictated by AT&T, which owned everything
 - Became a worldwide standard (almost)



■ Type B - Free markets

- Governed by (emergent) community standards
- Example: H.323 video format
 - Set up by Int'l Telecommunications Union (ITU)
 - Enables desktop conferencing (e.g., NetMeeting)



As discussed in the Domain Integration study, systems can connect to one another in a variety of ways. When systems have tight interdependencies, the connections often intertwine with fundamental behaviors inside each system that is being brought together. The so-called “tight coupling” implies detailed knowledge about each system and well-coordinated interfaces, which have many and complex ways of interacting to support the system-to-system interconnections. On the other hand, “loosely coupled” systems implies that there are some commonly understood rules of engagement that allow the systems to pass information without needing intimate knowledge about the internal operations of each system. These desirable loose couplings allow much flexibility among systems that are interoperating.

Several features of convergence protocols help define this important class of loose couplers. First, they must enable independent evolution of technology on each side of the protocol. Second, they are typically long-lived. Since many people build on them, they hence become essential elements over many generations of technological change. In the case of the Internet, IP, which was first implemented in the 1970s, remains the dominant network protocol in use today; connecting billions of devices of staggering variety.

Convergence protocols (and standards in general) can be developed in many ways. One common structure is the existence of a single entity that has control over the entire collection of technologies required to develop a given capability. A commercial example of this is the development of the RJ11 phone jack, which is the standard connection for telephones (and modems) in the US and most of the world. AT&T developed RJ11 and dictated this standard because it controlled the telephone market at the time. A second method by which convergence protocols and standards are developed is through free markets. This approach typically involves groups of companies, standards organizations, and other communities of interest coming together to find a mutually beneficial protocol. Often several different protocols emerge (Beta versus

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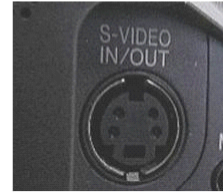
Vertical Helical Scan or VHS), and the market determines whether multiple protocols survive or whether one becomes the dominant protocol (VHS, IP, and so forth).

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Commercial vs DoD Markets




- Commercial systems of systems rely on future profit as incentive ⇒ incorporate standards
 - Consumers buy systems that can interact with other systems over time
 - Example: extra laptop features (USB, SVGA, 802.11x, Bluetooth)
- DoD pays for development of technology and cuts funding ⇒ develop specialized interfaces
 - Little incentive to include standard interfaces if they don't enable KPPs
 - Flexibility gets cut during budget crises
 - DoD will to pay to fix the problem later




SoS for DoD requires different approach


An important finding of the study is that the techniques for building an effective system-of-systems in the commercial world are not likely to work in the DoD. In commercial systems future profit provides an incentive for seeking and using convergence protocols. Hence, additional features may be included on a product because it will enable the system to become part of a system-of-systems later. In the DoD there is little incentive for including standard interfaces if they do not enable key performance parameters (KPPs). Although integration of standard interfaces is often present at the beginning of a program, program managers can cut features that add cost to the product later in the program as budget issues arise. The DoD exacerbates this situation by its willingness to pay later to fix the problem; when it would have been cheaper to address the problem by including the standard interface. Thus, we believe that enabling SoSE in the DoD will require a different approach.




If Convergent Protocols Were Available...

- **Joint Unmanned Combat Air Systems (J-UCAS)**
 - Currently developing a common operating system and demonstrator air vehicles
 - The development and evolution of requirements is stated as a critical element of the program
 - Emphasis is being placed on insuring intra-operability between planned and potential internal components
 - Similarly, emphasis is being placed to insure inter-operability with external elements such as manned aircraft, C2 centers, space assets, etc.
 - **Would convergence protocols allow for increased flexibility and adaptability?**
 - i.e., better system of system inter-operability and enhanced future capabilities







As described previously, convergent protocols are those protocols that allow systems to interact and communicate at key points across system boundaries. Imagine for a moment, if these protocols were available for the Joint Unmanned Combat Air Systems (J-UCAS) program. How would the existence of these protocols ease the programs burdens and provide for better system-of-systems operability?

The J-UCAS is currently developing a common operating system (COS) and two different air vehicles variants, the X-45 and X-47. The X-45 variant focuses on meeting Air Force mission requirements, while the X-47 variant addresses Naval missions. One of the main objectives of the program is the development and evolution of system level requirements. The systems and programs, which are a result of J-UCAS initiatives, will need to have elements of both intra- and inter-operability.

Well-defined system requirements and proper Systems Engineering will result in systems designed with a high degree of intra-system capability. This intra-system capability will result in system elements, such as radar sensors, electronic warfare components, and ground elements, which developers and users can interchange and upgrade to meet changing mission requirements. Additionally, this intra-operability greatly enhances the spiral development process, which is common in the current acquisition process.


Developing inter-operable systems pose another set of challenges. This is especially true when future needs are uncertain and it is unknown what specific systems will need to work together as a system-of-systems. If convergent protocols existed, it is likely that it would be easier to develop systems with the flexibility and adaptability to meet true system-of-systems inter-operability.

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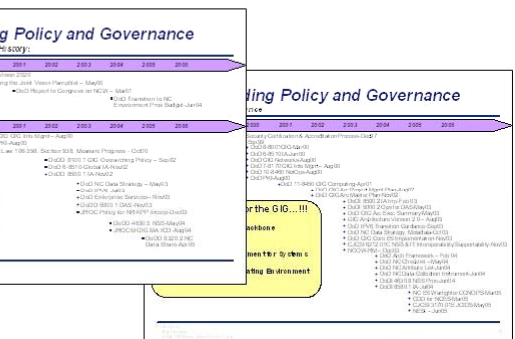
3.3. Motivations



Motivators

■ Lots of guidance exists on what should be done





But, no specifics exists on how to do it...

Next, we must explore the motivations for the participants in a system-of-systems development so that the Air Force can incentivize behavior towards cultivating more systems enabled for participation in systems-of-systems.

The traditional approach for the DoD to encourage adoption of commonality among systems is to issue a directive, instruction, or guidance, which forces program managers to conform. There is much guidance in the case of network centricity. The two small diagrams above include a calendarized list of documents released that declare the vision and provide guidance for program managers to adopt the Global Information Grid (GIG). It is healthy and good to describe the intended goals for achieving the benefits of network centricity.

However, the provided guidance is insufficient. The instructions are too vague for a program manager or contractor to incorporate with a successful outcome that transcends the Responsibility, Authority, Accountability, and Resources (RAAR) limits of his or her project. There is a need for a single entity to declare sufficient specificity among protocol candidate standards that everyone could apply the protocol as a Market Enabling Convergence Protocol.

The traditional DoD approach, to declare a solution and require everyone to conform, may surface with respect to convergence protocols prematurely. When this has happened in the past, the consequences have not been good. It is important not to declare guidance and directives for an unproven technology. Hence, we propose a different approach for the SoSE methodology. First, establish hands-on experience with the appropriate convergence protocols. Then, issue

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such guidance as appropriate for program managers. Do not do this in the opposite sequence (which appears to be the current path)

Note also, our suggestions are not about adopting a specific vendor's "product;" the methodology focuses upon a derived protocol implementation standard.

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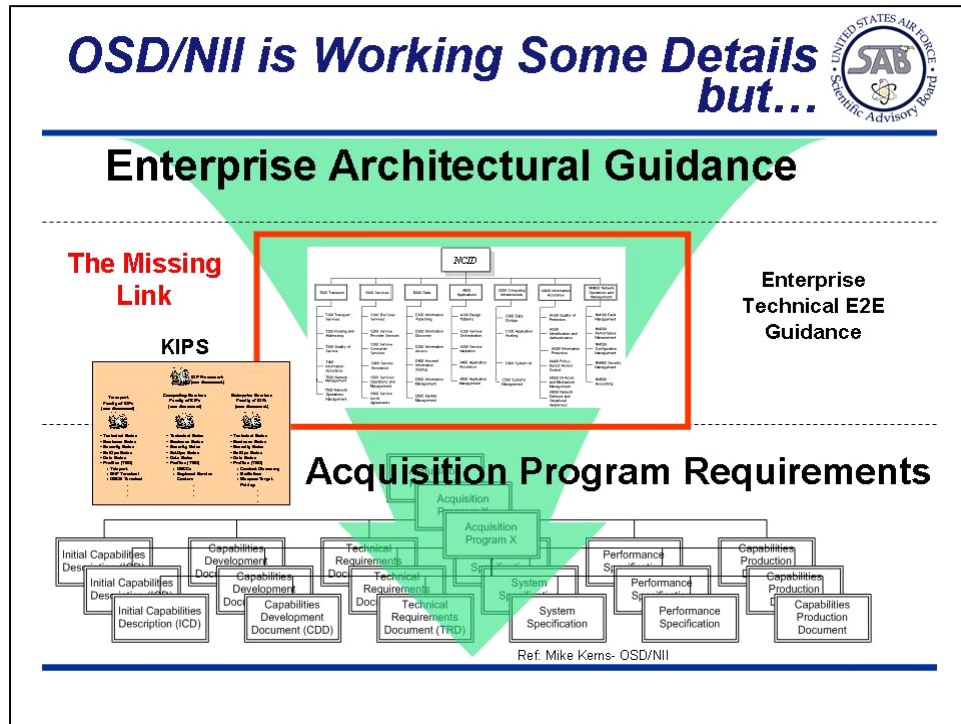
Motivators



- **Motivators are needed to encourage users to ask for, acquirers to procure and developers to deliver systems capable of working in an interoperable and adaptive systems of systems environment**
- **Motivators are different yet have a common basis for each group**
 - **Users - Desire to obtain maximum capability**
 - **Acquirers - Desire to meet user requirements**
 - **Developers - Desire to meet short and long term business goals, which can be tied to meeting user requirements**
- **What is needed is a way to determine the System of System derived requirements**

Given that commercial market forces are inappropriate for the DoD, some alternative motivational approach is necessary. Contrary to commercial practice where the developer speculatively invests in something, perhaps with total ignorance on the part of the user; the DoD user needs to express requirements for something. With regard to convergence protocols, neither program managers nor contractors can include them based on anticipated future needs; only the user can legitimately express the requirement.

Therefore, the SoSE strategy is to discover motivators for use within the DoD.

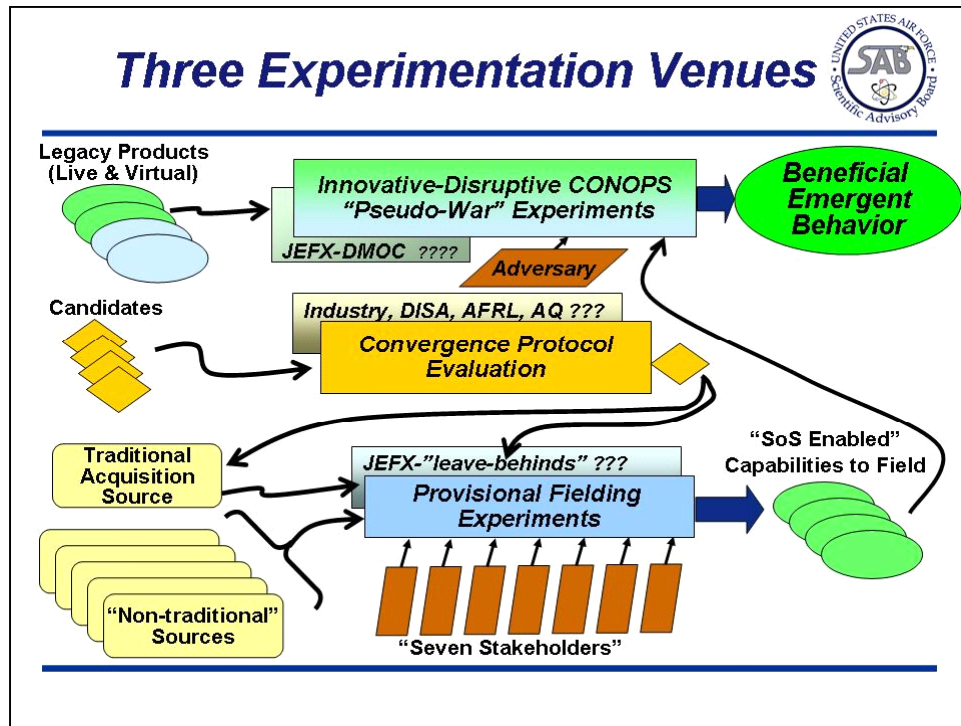


In the case of the GIG, there is an effort underway to express more specificity in terms of what the individual programs need to incorporate to be able to achieve system-of-systems interaction via the GIG. However, there is a “3-bears” problem: Too much detail and DoD over constrains systems, not enough detail, and the objective behavior is not met. Finding the “just right” level of detail can only be derived via experimentation. Unfortunately, the authors of these policy documents do not (yet) have the experimental laboratory or venue necessary to discover the right answer.

In other words, it is necessary to re-emphasize the cautionary note expressed earlier about premature declaration of standards. The people promoting more specific program manager instructions do understand the challenges faced by program managers with vague guidance; however, premature specific guidance could be harmful.

So, although this section began with somewhat disparaging remarks towards the volume of documented guidance, instructions, advice, and so forth, it ends with an endorsement of just that kind of activity (albeit with one substantial modification: Emphasis on experience born of experimentation). This leads us into the next and final discussion topic: Experimentation.

3.4. Experimentation



The commercial marketplace is an active environment in which one can continually test and evaluate emergent system-of-systems opportunities. On the other hand, the environment is mostly asleep (hopefully) for DoD products because war is never a preferred condition of operation. Nevertheless, it is during wartime when the most dramatic alterations to DoD (USAF) CONOPS take place. This suggests that there is a need for a “pseudo-war” experimentation venue to substitute for the active commercial market environment that drives commercial systems-of-systems. The absence of such an experimentation venue seems to cause stagnation of USAF capability aspirations around the achievements of the “last fought war.” Disruption of the status quo is an important ingredient in system-of-systems operation. Therefore, if the Air Force is to achieve the purposes of this study, it must find effective methods of disrupting the status quo.

With rare exception, most DoD SoS development has been initiated as “on the fly” intersystem couplings, enabling CONOPS that meet immediate wartime operational needs. While there is a plethora of DoD documentation espousing the value and need for SoS, DoD has mostly been unsuccessful in generating strong motivation to identify and develop SoS enablers during peacetime. Ingrained acquisition approaches and conventional SE methodology have not encouraged users, acquirers, and developers to adopt an SoS perspective in the design, development, and use of DoD systems.

A key recommendation of this study is to use robust experimentation to show the value of enabling SoS participation to system level users, acquirers, and developers. This experimentation would consist of three distinct venues:

Concept Experimentation – a mechanism for low-cost, low-entry barrier experimentation, with low consequence of failure, for developing new CONOPS for collections of existing systems and evaluating proposed systems and their impact on existing systems.

Intersystem Coupling Experimentation – a mechanism for ongoing development of intersystem couplers; identifying those that by their utility become convergence points that must be considered in the development of all future DoD systems.

Provisional Fielding – a mechanism for rapid experimental fielding of an emerging SoS concept that provides an initial capability, crystallizes user(s) requirements, and focuses the spiral development of the SoS component systems.

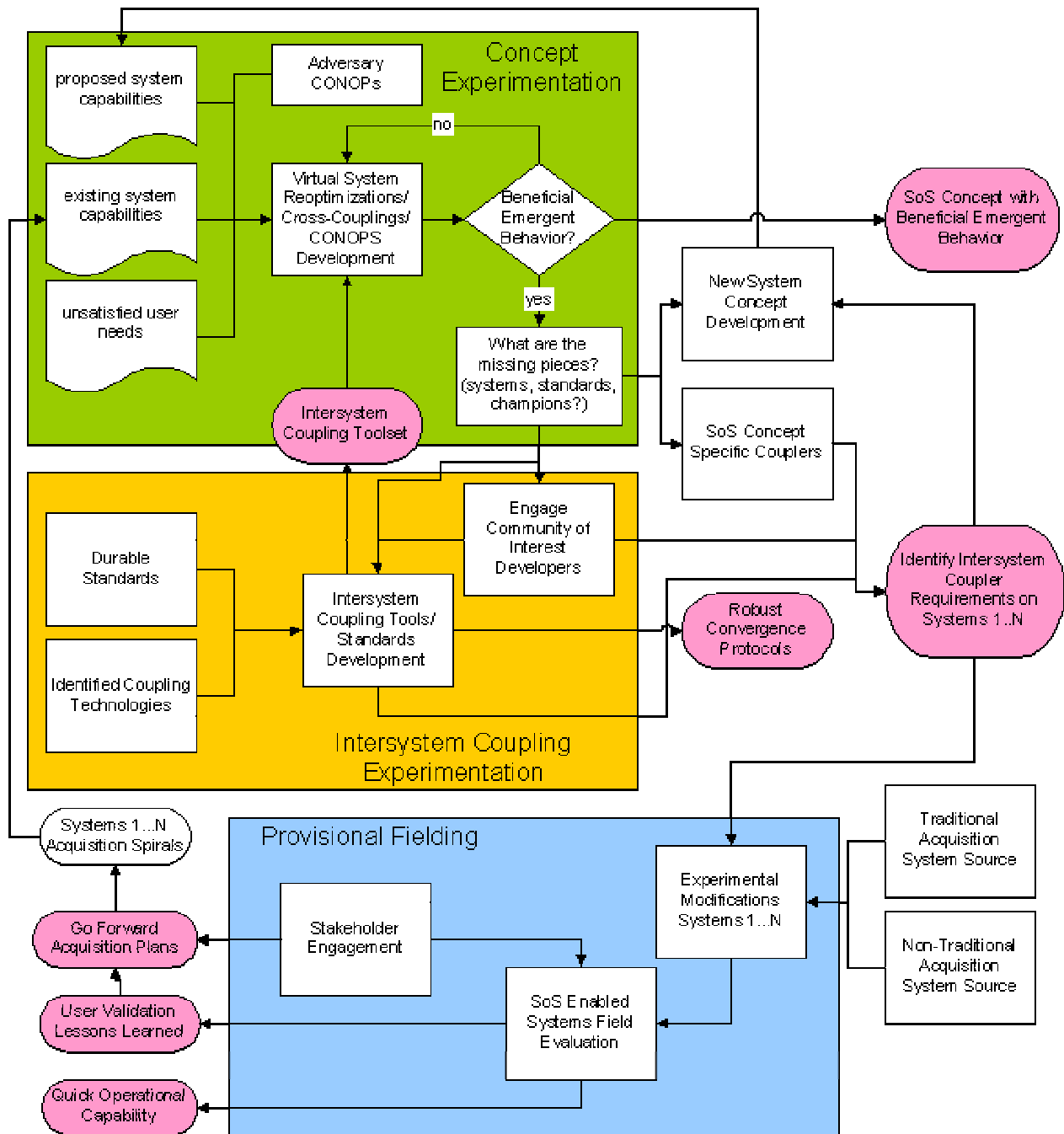


Figure 1: Three experimental venues for promoting SoS development

Figure 1 presents an SoS experimentation flow diagram illustrating for each of the three venues the kinds of efforts undertaken in each venue, the output products of each venue, and interconnections of efforts and output products for each venue. All three would occur in parallel,

providing feedback to one another to create an ongoing experimental “Petri dish” environment for SoS development.

This structure allows for a division of responsibility among USAF organizations, focusing attention and leadership in addition to better coupling research, acquisition, and operator interests early in the process of developing complex SoS.

For example, concept experimentation and SoS CONOPS development might best be “owned” by operators such as AF/XO or Air Combat Command (ACC). Intersystem Coupling Experimentation is of central value to organizations with integration responsibilities such as SAF/XC or because of its largely generic R&D character to Air Force Research Laboratory (AFRL). Provisional fielding might be the purview of SAF/AQ as the lead office.

Concept Experimentation

The first experimental venue for SoS exploration is that of Concept Experimentation. This venue would focus on exploring SoS architectures, developing SoS CONOPS, evolving the Tactics, Techniques, and Procedures (TTPs) of constituent systems, and experimenting with intersystem interactions to define SoS concepts that show beneficial emergent capabilities and operational utility beyond the “sum of the parts.” Making this a relatively low-cost and largely analytical exploration will provide a low entry threshold mechanism that the Air Force can promulgate as a continuous (i.e., peacetime) exercise and *evolve into an expectation* for:

- *Users* to investigate new CONOPS and explore SoS solutions to unmet or emerging needs;
- *Acquirers* to establish SoS communities of interest, i.e., which systems need to be procured with common downstream SoS convergence points (“hooks”) as an integral part of individual system developments; and
- *Developers* such as the Defense Advanced Research Projects Agency (DARPA), AFRL, and Contractors to identify and promote new mission concepts, discover fruitful evolution paths for existing systems, and test the efficacy of new systems in an SoS environment.

An essential element of concept experimentation is making it widely available to a broad spectrum of potential users through net-enabled access and low initial cost to play. This will expand the potential sources of SoS ideas beyond users in the field inventing “on-the-fly” to meet immediate wartime operational needs. Concept Experimentation will enable a broader exploration of SoS possibilities independent of the system specific trades that drive current system implementations by allowing experimenters to readily adjust the capabilities and CONOPS of existing systems through virtual re-optimization, and providing a means to couple in new systems without having to hardwire the couplings into existing systems.

Our recommendation is to extend current modeling and simulation capability to develop an SoS simulation environment that can bring together models of existing systems, simulations of proposed systems, live-fly exercises, and embodiments of adversary CONOPS; modify them to incorporate SoS enabling intersystem couplings; and evaluate resulting utility against identified user needs or new mission capability. For example, such an experimental environment could exploit existing networked modeling and simulation capabilities (e.g., DMOC, CWIN,

NCOIC facilities, and so forth). These facilities would make available models, or live versions, of existing systems for experimentation. The experiments would allow re-optimization of individual systems and intersystem coupling, unconstrained by tradeoff limitations that would normally affect individual systems in the real world.

In our vision an experimenter would have the equivalent of “pull down” menus for selecting component systems, intersystem couplers, adversary tactics, and basic mission structure (e.g., global strike and so forth). These can be “dragged and dropped” into a software environment through a graphic user interface that allows access to each component model for modification of system capabilities, CONOPS, and interfaces.

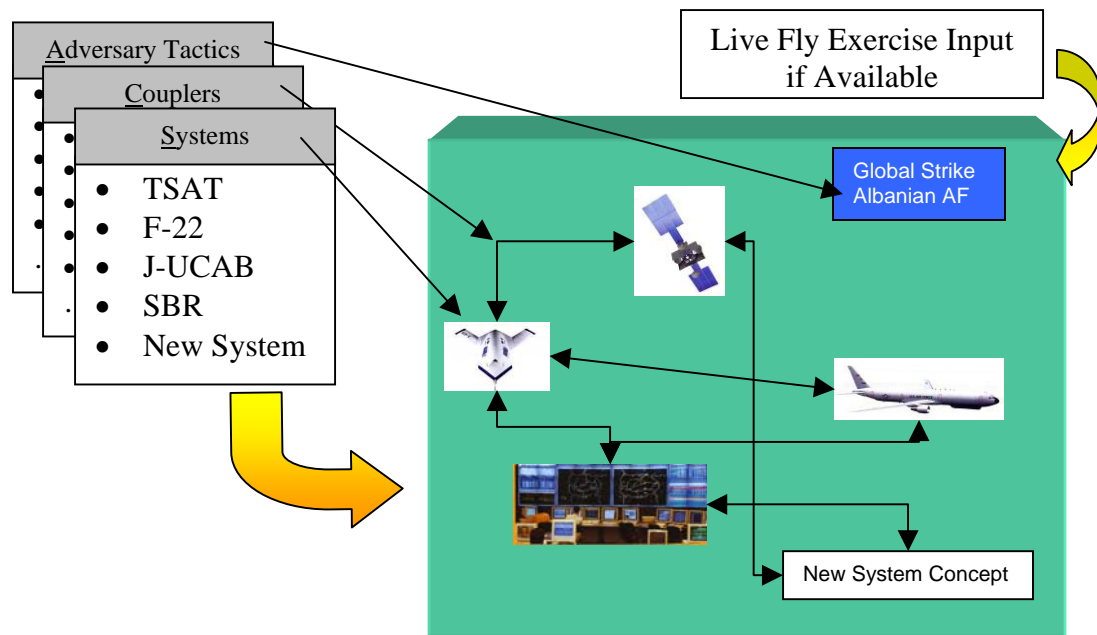


Figure 2: A virtual software wrapper for SoS concept experimentation

Different combinations of systems, using different intersystem couplers, flying missions against different adversaries can be implemented virtually in search of SoS emergent behavior.

A key product of concept experimentation is the identification of beneficial emergent behavior; the “why” that drives the SoS. Because SoS enabled systems invariably will incur additional costs, this set of emergent capabilities provides the key motivator for users to require the incorporation of SoS enabling hooks in the spiral development of each component system.

When an SoS concept is shown to have beneficial emergent behavior, the underlying question changes in nature to: “what’s missing?” Whether it is specific intersystem couplers, missing systems, or champions from within the Community of Interest (CoI) defined by the constituent systems, this leads to discussions with CoI developers on impacts of proposed couplers as well as investigations of any SoS concept specific couplers that need to be developed.

Intersystem Coupling Experimentation

The next experimental venue for SoS exploration is Intersystem Coupling Experimentation. An important element of experimentation is the development of integrating tools and hooks that enable intersystem interactions. These intersystem couplers provide a starting basis for possible intersystem interactions during concept experimentation. They are also the “plug-ins” that must be accommodated for rapid provisional fielding experiments.

Much of the experimentation in this venue is accomplished independently of the other two venues in the sense that it seeks to mimic the successful emergence of commercial SoS by identifying and developing durable coupling protocols and standards. Examples include data transfer protocols, communication waveforms, processing algorithms, logistics interfaces, system health statusing, capabilities broadcast, and a slew of network issues such as multi-level security and bandwidth management.

Experimentation in this venue will examine existing standards and protocols. This includes those in development as commercial standards or those that have already shown significant utility through widespread commercial implementation. Other intersystem couplings, which might be unique to DoD SoS, are also examined and developed as part of this effort. These two experimental paths generate a set of intersystem couplers that can be used as the tool set in Concept Experimentation (the “couplers” pull-down menu).

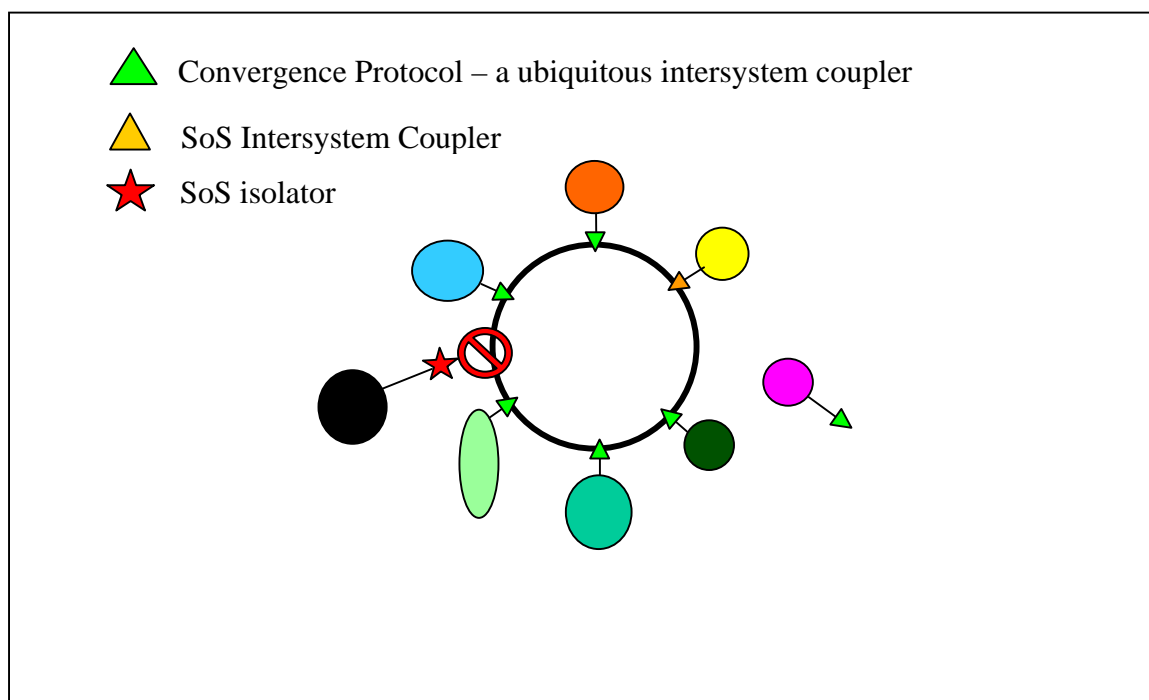


Figure 3: A Depiction of Three Intersystem Couplers

Figure 3 illustrates three classes of intersystem couplers available for development as part of this research thrust. There are intersystem couplers that are ubiquitous. Their utility and applicability are widespread in order to become standards that the Air Force must consider for all on-going system development, whether it is for new systems or spiral developments of existing systems. Examples include IP, High Level Architecture (HLA) for distributed computer simulation systems, and automobile hand controls. Other intersystem couplers exist that fall short of being a convergence protocol. However, these intersystem couplers still enable a system to participate in an SoS.

A third and important class of intersystem couplers are actually isolators; they serve to prevent a system from participating in a particular SoS. An example of an isolator is the narrow gasoline fill pipe for use with unleaded gasoline – the fill pipe prevents introduction of leaded fuel that would destroy the automobile's catalytic converter. Another example is electrical outlets; the plug serves to prevent an 110V, 60 Hz system from easily interfacing with a 220V, 50 Hz supply.

While it is envisioned that much of the experimental development of intersystem couplers will be to first order independent particular SoS architectures, there may be situations that call for development of more specific couplers, such as unique lines of code that interface legacy application specific software.

There are three key products of intersystem coupling experimentation. The first are protocols, standards, and other intersystem couplers that form the tool set for concept development and the plug-in hooks for rapid SoS field-testing. As these mature and the utility of particular intersystem couplers become more apparent, a second set of products, robust convergence protocols, evolves. The third product is the result of a more focused consideration of a particular SoS concept: a set of requirements on each component system for incorporating specific SoS enabling couplers. Since this could entail substantial downstream modification of a particular system's development path, the component systems development teams must participate in the development of this set of products.

Provisional Fielding

The third experimental venue for SoS exploration is provisional fielding. The purpose of this venue is to speed transition through rapid prototyping of SoS enabling intersystem couplers in a set of component systems. These experimentally modified versions of the systems can then be used for assessing the anticipated SoS benefit; discovering unexpected, beneficial, and detrimental consequences of the SoS coupling; and providing a "first spin" look at the impact on the constituent systems as independent elements. Each system gets a "taste" of what it needs to accommodate to achieve SoS interoperability, a definition of its development path and the benefit it derives.

Provisional fielding can incorporate systems developed through a traditional acquisition process or can integrate new systems in early development that have been generated through non-traditional approaches such as Tactical Exploitation of National Capabilities (TENCAP) and Big Safari. The intent is to integrate convergence protocols and/or other intersystem couplers as much as possible as "bolt-ons" with a goal of minimal invasiveness on the systems.

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Another element of provisional testing is engaging all stakeholders (users, developers, the acquisition community, testers, trainers, sustainment/logistics experts, and system level researchers) at an early stage in the eventual SoS development and deployment. Collectively they provide input that guides development of the primary products of provisional testing. A shortcoming in the past has been experimentation and early deployment that has not adequately addressed all of the stakeholder interests. For example, without adequate training coordination, initial capability can often disappear when the first users rotate out to other assignments. Sustainment/Logistics have a vital role in ensuring that system development pays heed to component “-ilities”: availability, serviceability, upgradeability, and so forth (Global Hawk example of obsolete parts).

Output products of the provisional fielding experimentation are user validation, initial operational capability, and an SoS driven acquisition plan. A primary focus of the entire experimentation process is to generate user enthusiasm that translates into user requirements for the SoS capability. Provisional fielding provides confirmation of value for community of interest users and validates concept generated users pull/requirements.

Provisional testing will also provide quick operational capability. Like what was envisioned as “left behinds” for JEFX, the set of SoS enabled systems (albeit at an early maturity stage) provides an initial operational capability and test-bed for further CONOPS experimentation. A third product is a “Go Forward” Development Plan, which is an updated user-driven requirements document that can feed a standard SE process for individual system upgrades.

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If SoS CONOPS and TTPs Were Available...



- **Joint Unmanned Combat Air Systems (J-UCAS)**
 - Program plans were to conduct a number of demonstrations and operational assessments
 - This is useful for future anticipated system of system constructs,
 - ... but does little to explore future capabilities and liabilities for unanticipated system of system constructs
 - A different type of experimentation venue needed to explore other system of system constructs?
 - i.e. develop new system concepts and associated CONOPS, TTPs and interfaces in a SoS environment
 - Challenging scenarios, non-designed for missions, willingness to fail



An example of a system development that could benefit from experimentation would be the J-UCAS program. The J-UCAS program plans to conduct several operational assessments (OAs) during the 2007-2010 timeframe. One of the goals of the OA is to demonstrate that DoD and the Air Force can fully integrate J-UCAS into the battlespace in a system-of-systems environment to achieve desired effects, not merely to act as a stand-alone entity. Two key areas for these assessments are communications/networking and vehicle mission control systems. This is an important activity, but it does not address the capabilities and liabilities associated with the system's ability to operate in unanticipated system-of-systems constructs. What is lacking is an experimentation venue focused on exploring non-traditional future scenarios where the Air Force needs other system-of-systems constructs to achieve the desired effects. Such an experimentation venue would allow for the development of system CONOPS, TTPs, and the necessary interfaces required to insure robust future system capabilities.

Developers and users should conduct experimentation in a challenging environment, not necessarily focused on the scenario and threats used for development of the initial system requirements, but in scenarios where they can tolerate failure as a means whereby they can learn lessons and better define future requirements. Combat experience shows that the Air Force uses systems and interoperates with other systems in ways not originally anticipated. Combat conditions can force users to develop interfaces and tactics to allow systems to interoperate in ways not originally anticipated. This experimentation would serve as a discovery and training venue, reducing the need to accomplish this under wartime conditions, thus resulting in a more capable and ready force.

Barriers...

- **Mythology**
 - **“Traditional” systems engineering processes**
 - The bureaucracy only knows one way to do things
 - **Need all resources focused on proficiency “Training”**
- **Reality**
 - **FAR, DoD 5000.2, etc. all emphasize satisfying “User Requirements”**
 - **Training needs to be balanced with Innovation**
 - innovation is really a form of training...
 - we always use innovation in combat; people need training in how to innovate with discipline
- **Technology**
 - **Need “discovery” mechanisms to achieve full Network Centric Operations**
 - **Need means of quickly identifying, converging, and promulgating the protocols that enable system-of-systems interoperation**

For any innovation there are usually barriers to overcome. In the case of the proposed SoSE methodology, the first barrier is tradition. The incorporation of experimentation venues for refining requirements and for accelerating product fielding runs counter to the existing culture. It is, therefore, important for the bureaucracy to not resist the idea of becoming involved in creating and facilitating the new concept. Having experts from each of the affected stakeholder organizations review and refine the methodology can help.

The second barrier is limited resources. The need for investment in training continues. It is not appropriate to send inadequately trained people into combat situations. However, one aspect of successful combat operation is the ability to deal with innovation. Hence, the new methodology recommends incorporation of “disruptive-innovation” in the training and experiment process for just that reason: To prepare warfighters for the changing conditions of combat.

Lastly, there are some technology shortfalls. The most notable is the absence of discovery mechanisms for information systems networks. Just being “on the network” does not achieve the vision of network centricity. Systems participating as a system-of-systems need to be able to discover the existence of information relevant to their mission without having that relationship preprogrammed several years prior to a wartime event. Information and service discovery needs to be managed “on the fly” at a pace that coincides with the “pick-up game” relationships that are often experienced in combat.

The other technology shortfall is the refinement of convergent protocols necessary to support system-of-systems interactions. Currently multiple competing middleware solutions exist from various agencies, programs, and services (e.g., the Distributed Common Ground Systems (DCGS) Integration Backbone, Future Combat Systems (FCS) System-of-Systems Common Operating Environment, Air Operations Center (AOC) web services, IBM web-sphere

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used in support command and control systems, Hewlett-Packard's products, and so forth). Successful achievement of system-of-systems enablement will require convergence of these multiple options down to a small set (or even only one set) of protocols that allow information discovery, access, and utilization among systems. In other words, merely providing "access" via a network is insufficient. More effort is required for the protocols to converge.

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4. Research Directions

As described in the previous sections, System-of-Systems Engineering is not yet a well-defined practice, let alone a formal discipline. Over the long-term, it is clear that SoSE must evolve to such a discipline if we wish to effectively conceive, design, implement, and operate interoperable systems that enable new Air Force and DoD capabilities.

We can compare the current state and its future to the Systems Engineering discipline in the 20th century. Initially, complex systems were built through trial and error, with many failures. Eventually exciting new products and capabilities resulted. As the field matured, modeling and simulation played a greater role, enabled by the quantification of system performance and properties. This encouraged more rapid (and cheaper) development of systems, at higher levels of complexity. Finally, a discipline of Systems Engineering evolved. This allowed for the codification of the process required to determine and to manage system requirements. This in turn evolved into standard training courses for engineers. Today, we are able to develop systems that have levels of performance, robustness, and efficiency previously thought not possible. Military aircraft and spacecraft are excellent examples of the achievements of the overall Systems Engineering discipline.

The recommendations of this report reflect our belief that SoSE is not yet a discipline, and hence experimentation will be required to make progress in the short-term. However, over the long-term, additional investments in SoSE research are required to create a *predictive* engineering discipline. Academia, government, and industry will carry out this research. In addition, to achieve success, this research must likely couple these players.

A first step is research aimed at quantifying and understanding the relationships of a new set of “-ilities”. These new “-ilities” include flexibility, reconfigurability, evolvability, emergence, subscribe-ability, and others. Metrics and analytic tools that capture the “designer’s intent” will allow better consideration of these properties in the design process, as well as appropriate trade-offs that are central to good engineering design. A related area of inquiry seeks to understand how to exploit the DoD value chain in creation of SoSs as contrasted with the commercial value chain that is driven by different motivators and business models.

A second area of research is the development of a framework and tools for helping identify convergence protocols. As highlighted in the last section, convergence protocols are an enabler for rapid innovation and parallel development of interoperable technologies that lead to unanticipated synergies. New approaches are required to understand how to model systems-of-systems at an appropriate level of abstraction in which such convergence protocols can be identified and evaluated. If such tools can be developed, they will allow us to move from a reliance on experimentation (or market-forces for commercial applications) to a more analytical basis for understanding tradeoffs and selecting standards that will become convergence protocols.

Finally, an important element of System-of-Systems Engineering for DoD systems is the human element. Research in human system interaction (HSI) and decision-making is required to understand better how to integrate these elements into an effective system-of-systems architecture.

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The traditional research environment does not effectively support large scale, transdisciplinary research; yet such research is critical to developing the discipline of SoSE. The traditional research environment emphasizes disciplines, but the issues that the Air Force faces do not break along clean disciplinary lines. Rather SoSE research demands a high degree of collaboration between government, industry, and academia. It requires new approaches to how the Air Force allocates research funds, how research partners collaborate, and how the Air Force can fully realize research synergies.

Research in SoSE involves experimentation, modeling and simulation, as well as field studies that contribute to new knowledge on the optimal structures and behaviors of complex systems-of-systems. The Air Force can transition this research to practice in the form of new methodologies and enabling technologies, as well as the development of case studies for use in educating the workforce. The desired impact of the research is knowledge and enabling practices and technologies for developing SoSs with outcomes that are more predictable.

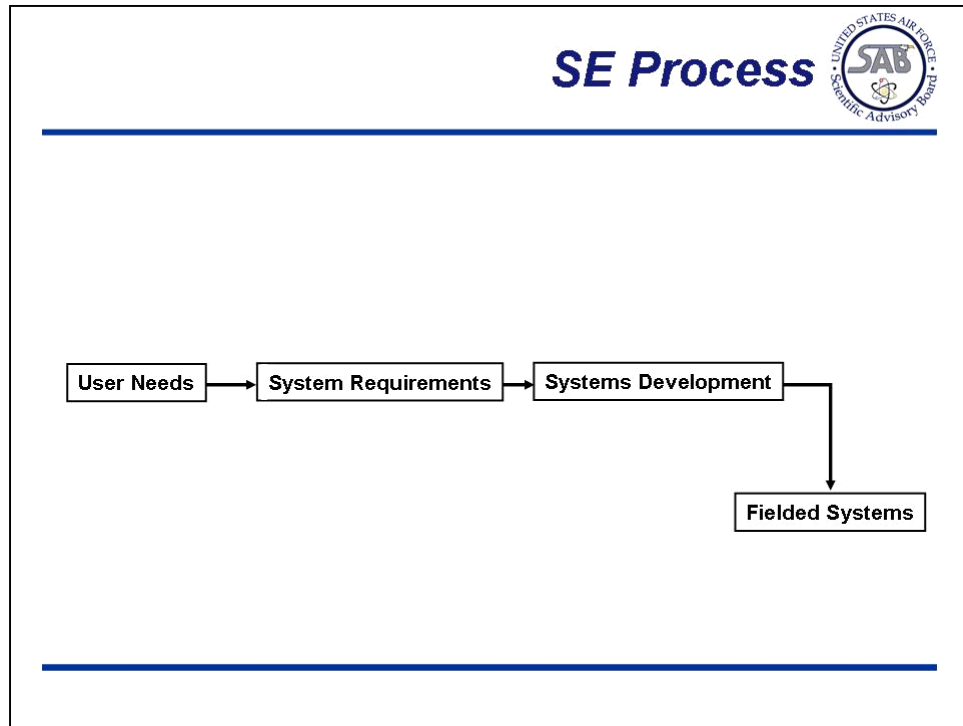
The research agenda is still emerging for SoSE; however, research is already underway at some leading universities, working in partnership with government and industry. Several universities have established crosscutting programs, research partnerships, and new types of laboratories to tackle the challenges of systems-of-systems.

While not the focus of this report, the reader should note that the effective implementation of the SoSE process depends upon the enabling environment to support it. This includes acquisition practices that are suited to the nature of the SoS, technologies and toolsets that enable engineers to perform SoSE, and solving some of the pragmatic business concerns related to SoS endeavors.

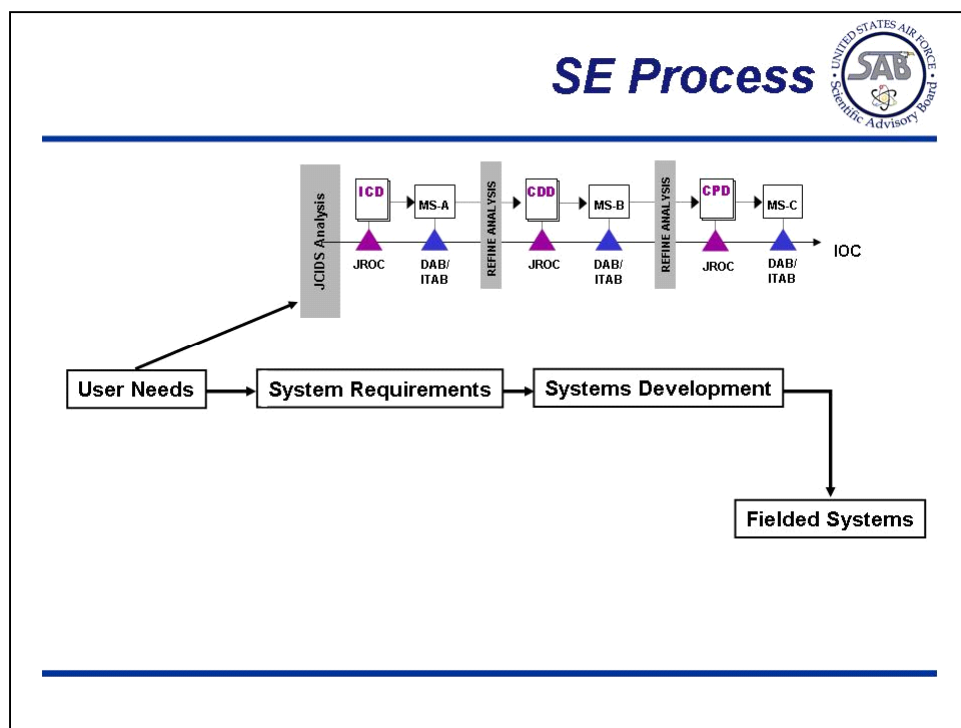
Many enablers already exist. However, we need more before we can realize the SoSE vision. Enablers include the many policies and guidance documents promoting the importance of SE and SoSE and various standards and guidance documents that have improved architecting and engineering practices. There is also a shared mindset that good Systems Engineering processes need to be applied to the component systems in the SoS.

Many barriers exist, the first of which is that there is not yet a prevailing mindset that SoSE is more than traditional SE applied to a larger system; we must overcome this as a first step to a robust SoSE discipline. Many of the present acquisition practices, while very effective for traditional SE, demand levels of detail or levels of technology readiness too early in the life cycle for an SoS. New practices are needed that will ensure the necessary level of control, but will better accommodate the (necessary) uncertainty involved in SoSs. Another barrier is the lack of protocols and a modeling environment for pulling together independently generated system models so that these can interact together in larger scale experimentation. Some very significant barriers exist that are rooted in the realities of the competitive marketplace. We lack the strategies for dealing with IP issues and competitive advantage concerns in the complex SoS endeavors where many organizations are collaborating in a way where open technical exchange is essential to success. We need additional studies to understand SoS enablers and barriers more fully.

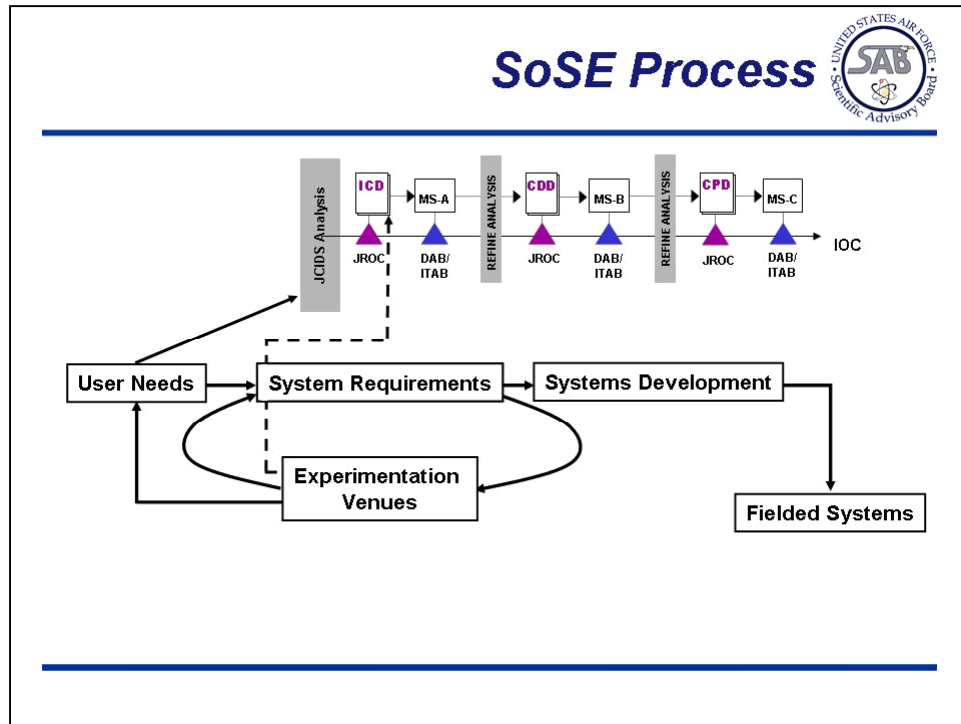
5. Summary



Shown here is the current system development process. This process starts with a clear understanding of the military user needs from which system requirements are derived. It is well recognized that system requirements play a preeminent role in the Systems Engineering process and subsequent acquisition processes that lead to a fielded capable system.

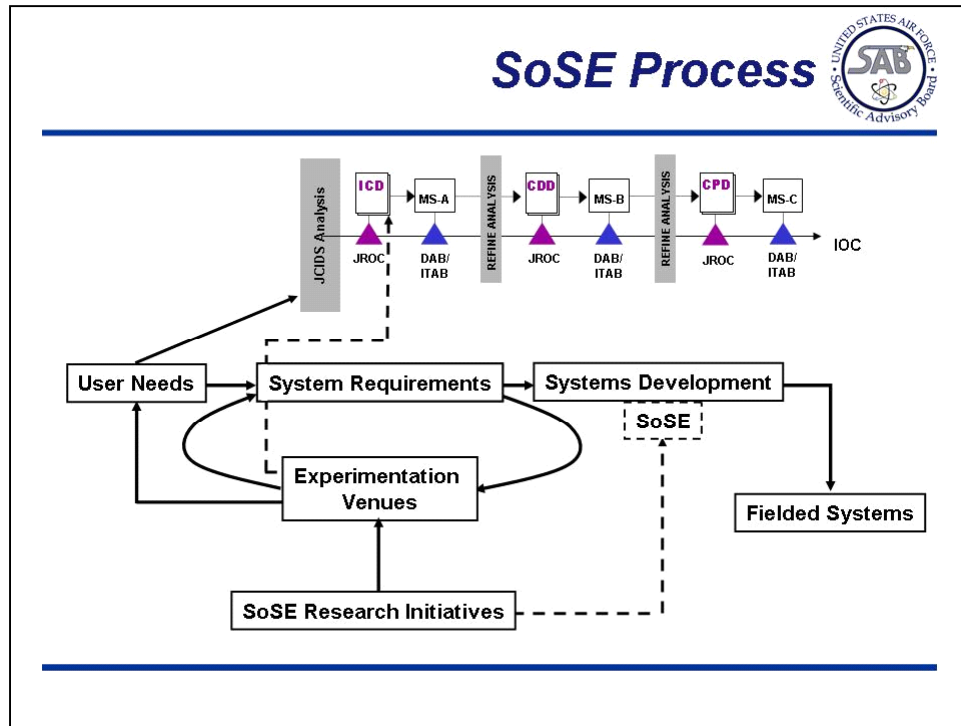


The acquisition of any weapon system is a complicated process. The Joint Capabilities and Integration Development System (JCIDS) focuses on identifying user needs and conducting the necessary analysis to determine the best material or non-material means to overcome an identified capabilities gap. The JCIDS process also focuses on meeting joint warfighter requirements and closely integrates with major milestone decisions.



We propose experimentation venues as a means for achieving pragmatic near-term results. As previously described, these venues should support disruptive and innovative CONOPS experiments, convergence protocol evaluation and selection, and support for rapid provisional fielding of SoS enabled systems. Also from a pragmatic approach, technology that provides discovery among systems and makes association of information needs among the publishers and subscribers is necessary to achieve the full potential of network centric operations.

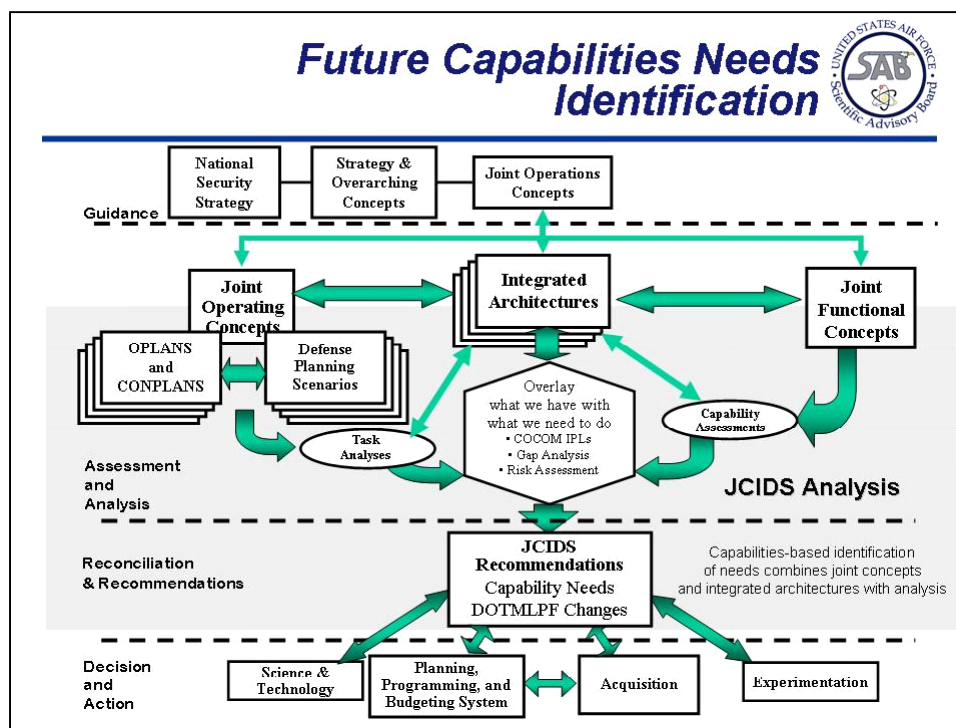
The addition of an experimentation venue to the process will allow for the development and articulation of user needs specially focused on achieving system-of-systems capabilities. The lessons learned from the experimentation venue will drive user needs as well as specific system requirements, which can assist the JCIDS process by providing experimentation derived user requirements to support the development of the Initial Capabilities Document (ICD). As shown here, the suggested SoSE processes are compatible with, but not dependent upon, the JCIDS process. Thus, while JCIDS can benefit from SoSE, the SoSE processes will continue as a meaningful and vital part of systems development even if DoD replaces JCIDS with something else.



To encourage the use of SoSE, the government should undertake specific SoSE research initiatives to promote investigation within this topic. There are aspects of such investigation that would be applicable to both commercial and DoD environments, but there are some aspects of such investigation that must be focused on DoD (and USAF) unique constraints. The differences in the enterprise environment between commercial interests and DoD legal constants can have a profound effect upon the direction of research. Only DoD sponsored research is likely to produce results that are usable within DoD.

The results from these research initiatives will directly feed into the experimentation venues such that the results of the initiatives can be tested and evaluated in a system-of-systems environment complete with user involvement allowing for the development of new enabling CONOPS and TTPs.

Research initiatives that are focused on further developing System-of-Systems Engineering as a practice, and ultimately as a discipline, will further enhance the system development process, by developing a true System-of-Systems Engineering process.



The fundamental change in JCIDS from the previous requirements system is to base it on a top-down analyses rather than a bottom-up requirements generation.

The JCIDS analyses result from the national security strategy and overarching concepts. From these overarching concepts, joint operating concepts and functional concepts result along with integrated architectures that pull together these concepts and the associated systems.


The intent of this top-down approach is to identify capability gaps, ensure development of new capabilities within a joint warfighting context, and increase the number of systems that are actually “born joint” in the first place.

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6. Recommendations



Recommendations

- Enable experimentation
 - Experiment for CONOPS development... to build innovative TTPs, and to build trust among cross domain participants (Action: AF/XO?, ACC?)
 - Experiment for infrastructure advances... sort out the implementable technology for the middleware layer that enables DI (Action: SAF/AQ? AFRL? SAF/XC?)
 - Experiment venue as a transition venue.... Allow “provisional” fielding (Action: SAF/AQ?)
- Pursue technologies for SoS (Action: AFRL/CC)
- Support research into theory and discipline of SoSE (Action: AFOSR)
- Form an IPT with membership from each of the USAF stakeholders (ACC, AFSPC, SAF/AQ, AFOTEC, AETC, AFMC, AFRL) to influence internal management practices that foster the new SoSE Methodology (Action: SAF/XC)

A Pragmatic Approach to SoSE...

There are four recommendations from the study.

First, set up three experimentation venues under the auspices of three different organizations. It is important that there be separate organizations owning the experimentation venues so that each venue preserves its identity. The purposes for which the venues serve need separate sponsorship and advocacy. On the other hand, it is also important for the three venues to work together. The interplay among each experimentation venue enables the effective operation of the other two. We recommend Air Combat command and the Deputy Chief of Staff of the Air Force for Plans and Operations (AF/XO) pursue the CONOPS experimentation venue. The Air Force Research Lab, the Assistant Secretary of the Air Force for Acquisition (SAF/AQ), and Secretary of the Air Force, Office of Warfighting Integration and Chief Information Officer (SAF/XC) should work together to pursue infrastructure experimentation. SAF/AQ should also pursue experimentation for provisional fielding.

Second, pursue the two technologies described in the report. Discovery agents are necessary to enable network centricity versus merely network enablement. Moreover, disciplined evaluation of convergence protocols is necessary to identify the expected standards for implementation in every system that is to be “system-of-systems enabled.” We recommend responsibility for this go to the Commander, Air Force Research Laboratory (AFRL/CC).

Third, invest further in the underlying theory of interactions among systems to accomplish the predictable analysis of systems engineered as part of a system-of-systems. This reflects the strong pragmatic perspective of this report and the resultant methodology. We believe responsibility for this should go to the Air Force Office of Scientific Research (AFOSR).

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Fourth, assemble an integrated product team (IPT) of the affected bureaucracies to refine this recommended methodology so that the bureaucracies can incorporate the methodology within their respective organizations. We recommend that SAF/XC should take responsibility for forming the IPT. Further, we recommend that IPT membership should include the following:

Air Combat Command (ACC)

Air Force Space Command (AFSPC)

Assistant Secretary of the Air Force for Acquisition (SAF/AQ)

Air Force Operational Test and Evaluation Center (AFOTEC)

Air Education and Training Command (AETC)

Air Force Materiel Command (AFMC)

Air Force Research Laboratory (AFRL)

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Appendix A: Terms of Reference

USAF SCIENTIFIC ADVISORY BOARD 2005 QUICK LOOK STUDY

System-of-Systems Engineering for Air Force Capability Development

Terms of Reference

BACKGROUND

Inadequate application of Systems Engineering principles and processes is the rationale used to explain why acquisitions are behind schedule, over budget, and deficient in required functionality. Yet, the current state of systems engineering does not adequately support the development of complex, adaptive, and software-intensive system-of-systems (SoS)⁴ in which humans are parts of the system. While capabilities-based justification of operational need, such as supported in the CRRA process, is a step in the right direction, there is no well-established SoS methodology and associated tools and techniques that can support faster engineering analysis and realization of required capabilities. We need a methodology that can match operational tempo – that can quickly field ‘good enough’ systems that can be further developed and supported concurrent with their operational test and use. The existing tools and processes are often focused on a very limited number of narrow, pre-defined alternatives and lack the fidelity, agility, and integration necessary to provide responsive, comprehensive analysis of alternatives. The Air Force needs to build an understanding of the critical developmental and research needs in the (system) engineering of systems-of-systems.

STUDY PRODUCTS

Briefing to SAF/OS & AF/CC by August 2005. Publish report by December 2005.

CHARTER

This quick look study will propose an engineering methodology, tailored for use by the Air Force, for software intensive SoS development with the dual goals of engineering a robust and adaptable SoS that:

- (1) Provides validated operational capabilities; and
- (2) Is delivered at a cycle time synchronous with current operational tempo.

The engineering methodology will leverage:

- (1) Existing (and sometimes unused) sound systems engineering principles,

⁴ A system will be called a System-of-Systems (SoS) when:

- The component systems achieve well-substantiated purposes in their own right even if detached from the overall system;
- The components systems are managed in large part for their own purposes rather than the purposes of the whole;
- It exhibits behaviors (including emergent ones) not achievable by the component systems acting independently;
- Functions, behaviors and component systems may be added or removed during its use.

Appendix A: Terms of Reference (continued)

- (2) Existing (and sometimes very successful) creative, non-traditional, innovation driven acquisition processes,
- (3) Operator derived expectations for systems engineering outcomes as exhibited among warfighters with field experience on SoS solutions, and
- (4) Evolving research results in executable, model-based architecture to support concurrent discovery of requirements, simulatable and testable SoS representations, analysis and design of SoS architecture, and rapid transformation into fieldable capabilities.

The study will be scoped to focus on an exemplar area based on Air Force needs: e.g., (1) the integration of information operations capabilities into the CAOC; or (2) use of modeling and simulation for joint operational testing.

Appendix B: Study Members

Study Leadership

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Study Panel

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Dr. John Brock

Mrs. Natalie Crawford

Dr. Mica Endsley

Mr. Ed Glasgow

Dr. Dan Hastings

Prof. Alex Levis

Prof. Richard Murray

Dr. Donna Rhodes

Dr. Marvin Sambur

Ms. Heidi Shyu

Mr. Phil Soucy

Dr. David Whelan

General Officer Participant

Lt Gen (S) Charles Croom, USAF

Study Management

Maj Christopher Berg, USAF – Project Manager

Maj Alan Seraile, USAF – Executive Officer

Maj David Herring, USAF – Technical Writer

Mr. Justin Waters – Analyst

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Appendix C: Acronyms and Abbreviations

ACC	Air Combat Command
AETC	Air Education and Training Command
AF	Air Force
AF/XO	Deputy Chief of Staff of the Air Force for Plans and Operations
AFC2ISRC	Air Force Command, Control, Intelligence, Surveillance, and Reconnaissance Center
AFMC	Air Force Materiel Command
AFOSR	Air Force Office of Scientific Research
AFOTEC	Air Force Operational Test and Evaluation Center
AFRL	Air Force Research Laboratory
AFRL/CC	Commander, Air Force Research Laboratory
AFSPC	Air Force Space Command
AOC	Air Operations Center
Arc, Arch	Architecture
AT&L	Under Secretary of Defense for Acquisition, Technology, and Logistics
AT&T	American Telephone and Telegraph
BLUF	Bottom Line Up Front
C2	Command and Control
C4ISR	Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance
CAIG	Cost Analysis Improvement Group
CDD	Capability Development Document
CIO	Chief Information Officer
CJCSI	Chairman Joint Chief of Staff Instruction
COCOM	Combatant Command, Combatant Commander
CONOPS	Concept of Operations
CONPLANS	Contingency Plans
CPD	Capability Production Document
CWIN	Cyber Warfare Integration Network
DAB	Defense Acquisition Board
DARPA	Defense Advanced Research Projects Agency

Appendix C: Acronyms and Abbreviations (continued)

DAS	Defense Acquisition System
DCGS	Distributed Common Ground Systems
DII-COE	Defense Integration Infrastructure - Common Operating Environment
DISA	Defense Information Systems Agency
DMOC	Distributed Mission Operations Center
DoD	Department of Defense
DoDD	Department of Defense Directive
DoDI	Department of Defense Instruction
DOTMLPF	Doctrine, Organization, Training, Materiel, Leadership & education, Personnel & Facilities
DSP	Defense Support Program Satellite
DVD	Digital Video Disc
E2E	End-to-End, Enterprise-to-Enterprise
ES	Enterprise Services
ESC	Electronic Systems Center
ESC-CC	Electronic Systems Center-Commander
ESC-EN	Electronic Systems Center-Engineering
FAR	Federal Acquisition Regulations
FCS	Future Combat Systems
FFRDC	Federally Funded Research and Development Center
FTP	File Transfer Protocol
GIG	Global Information Grid
HD	High Definition
HDLC	High-level Data Link Control
HLA	High Level Architecture
HSI	Human Systems Interaction
HTTP	Hyper Text Transfer Protocol
Hz	Hertz
IA	Information Assurance
ICD	Initial Capabilities Document
IEEE	Institute of Electrical & Electronic Engineers

Appendix C: Acronyms and Abbreviations (continued)

IETF	Internet Engineering Task Force
Imp	Implementation
IOC	Initial Operational Capability
IP	Internet Protocol
IPL	Integrated Priority List
IPT	Integrated Product Team
IPv6	Internet Protocol version 6
IT	Information Technology
ITAB	Information Technology Acquisition Board
ITU	International Telecommunication Union
JB	Joint Battlespace Infosphere
JCIDS	Joint Capability Integration & Development System
JEFX	Joint Expeditionary Force Experiment
JPEG	Joint Photographic Experts Group
JROC	Joint Requirements Oversight Council
JROCM	Joint Requirements Oversight Council Memorandum
J-UCAS	Joint Unmanned Combat Air Systems
KIPs	Key Interface Profiles
KPP	Key Performance Parameter
KPPs	Key Performance Parameters
MA	Mission Area
MS-A	Milestone A
MS-B	Milestone B
MS-C	Milestone C
NC	Net Centric, Netcentric
NCID	Net-Centric Implementation Document
NCOIC	Network Centric Operations Industry Consortium
NCOW-RM	Net-Centric Operations and Warfare
NCW	Network Centric Warfare, Net Centric Warfare
NEI	Netcentric Enterprise Solutions for Interoperability
NetBEUI	NetBIOS Extended User Interface

Appendix C: Acronyms and Abbreviations (continued)

NetOps	Network Operations
NII	Assistant Secretary of Defense for Networks and Information Integration
NR-KPP	Net-Ready Key Performance Parameter
NSS	National Security System, National Security Strategy
OAs	Operational Assessments
OEF	Operation Enduring Freedom
OPLANS	Operations Plans
Ops	Operations
OSD	Office of the Secretary of Defense
PA&E	DoD Office of Program Analysis and Evaluation
PKI	Public Key Infrastructure
R&D	Research and Development
RA	Resource Analysis, Risk Assessment
RAAR	Responsibility, Authority, Accountability, and Resources
RJ11	Registered Jack 11
SA	Situational Awareness
SAB	Scientific Advisory Board
SAE	Society of Automotive Engineers
SAF/AQ	Assistant Secretary of the Air Force for Acquisition
SAF/AQRE	Assistant Secretary of the Air Force for Acquisition, Deputy Assistant Secretary (Engineering and Technical Management Division)
SAF/XC	Secretary of the Air Force, Office of Warfighting Integration and Chief Information Officer
SE	Systems Engineering
SMTP	Simple Mail Transfer Protocol
SoS	System-of-Systems
SoSE	System-of-Systems Engineering
SVGA	Super Video Graphics Array
TCP	Transmission Control Protocol
TCP/IP	Transmission Control Protocol/Internet Protocol
TENCAP	Tactical Exploitation of National Capabilities
TTPs	Tactics, Techniques and Procedures

Appendix C: Acronyms and Abbreviations (continued)

UDP	User Datagram Protocol
USAF	United States Air Force
USB	Universal Serial Bus
V	Volt
VHS	Vertical Helical Scan (or as JCV calls it, "Video Home System")

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Appendix D: Visits and Briefings

Air Force

Deputy Assistant Secretary of the Air Force for Science, Technology, and Engineering
Air Combat Command
Air Force Space Command
Air Force Command, Control, Intelligence, Surveillance, and Reconnaissance Center
Air Force Electronic Systems Center

Department of Defense

Under Secretary of Defense for Acquisition, Technology, and Logistics
Assistant Secretary of Defense for Networks and Information Integration
Office of Program Analysis and Evaluation, Cost Analysis Improvement Group
Missile Defense Agency

Department of Homeland Security

U.S. Coast Guard

Federally Funded and Non-Profit Organizations

The Aerospace Corporation
The MITRE Corporation
System of Systems Engineering Center for Excellence (SoSE Conference)

Industry

The Boeing Company
Lockheed Martin Corporation
Northrop Grumman Corporation

Universities

California Institute of Technology
George Mason University
Massachusetts Institute of Technology
Old Dominion University
Purdue University
Stevens Institute of Technology
University of California San Diego
University of Southern California
University of Virginia

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Appendix E: Initial Distribution

Air Force Leadership

Secretary of the Air Force

Chief of Staff of the Air Force

Under Secretary of the Air Force

Vice Chief of Staff of the Air Force

Air Force Secretariat

Assistant Secretary of the Air Force for Acquisition

- Deputy Assistant Secretary of the Air Force for Science, Technology, and Engineering
- Secretary of the Air Force, Office of Warfighting Integration and Chief Information Officer
- Air Force Command, Control, Intelligence, Surveillance, and Reconnaissance Center

Air Staff

Assistant Vice Chief of Staff of the Air Force

Deputy Chief of Staff of the Air Force for Air and Space Operations

Deputy Chief of Staff of the Air Force for Plans and Operations

Deputy Chief of Staff of the Air Force for Plans and Programs

Deputy Chief of Staff of the Air Force for Test and Evaluation

Director of the Air National Guard

Chief of Air Force Reserve

Chief Scientist of the Air Force

Scientific Advisory Board Military Director

Air Force Major Commands

Air Combat Command

- ACC Chief Scientist

Air Education & Training Command

Air Force Materiel Command

Air Force Reserve Command

Air Force Space Command

- Space Warfare Center

Air Force Special Ops Command

Air Mobility Command

Pacific Air Forces

U.S. Air Forces in Europe

Appendix E: Distribution (continued)

Other Air Force Elements

Aeronautical Systems Center
Air Force Electronic Systems Center
Air Force Institute of Technology

- Center for Systems Engineering

Air Force Office of Scientific Research
Air Force Operational Test and Evaluation Center
Air Force Research Laboratory
Air Warfare Center
Space and Missile Systems Center

Office of the Secretary of Defense

Under Secretary of Defense for Acquisition, Technology, and Logistics
Assistant Secretary of Defense for Networks and Information Integration
Office of Program Analysis and Evaluation, Cost Analysis Improvement Group

Joint Chiefs of Staff

Joint Chiefs of Staff, Director of C4 Systems
Joint Chiefs of Staff, Director of Operational Plans and Interoperability

Defense Agencies

Defense Information Systems Agency
Missile Defense Agency

Advisory Boards

Army Science Board
Defense Policy Board
Defense Science Board
Naval Research and Advisory Committee
Naval Studies Board

Department of Homeland Security

U.S. Coast Guard

Federally Funded and Non-Profit Organizations

The Aerospace Corporation
The MITRE Corporation
System of Systems Engineering Center for Excellence

Appendix E: Distribution (continued)

Industry

The Boeing Company
Lockheed Martin Corporation
Northrop Grumman Corporation

Universities

California Institute of Technology
George Mason University
Massachusetts Institute of Technology
Old Dominion University
Purdue University
Stevens Institute of Technology
University of California San Diego
University of Southern California
University of Virginia

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ABSTRACT (Maximum 200 Words) <i>System-of-Systems Engineering for Air Force Capability Development:</i> <p>Over the past several years, it has become increasingly apparent that although the United States Air Force buys systems in isolation, it does not use systems in isolation. An ever-changing mix of systems, which enable their warfighting capabilities, supports the missions of the Air Force. In an ideal world, the Air Force would build each system involved to satisfy specific and well-understood requirements. Then, each system would fit into its pre-established USAF role supporting whatever capability military leaders called upon for action. The reality is that the Air Force does not build all systems through a homogenous acquisition and development process, it does not use all systems in ways foretold at their inception, and not all systems find themselves used among predicted interface partners. Especially in wartime, the exigencies of war sometimes force a reconfiguration among systems or even demand systems behave in ways that create new capabilities. When such changes occur, the users in the field oftentimes find the tasks associated with reengineering interconnections among systems falls upon them. Increasingly, awareness of the need to support fungible interconnection among systems has driven the Air Force and systems engineers to start thinking about the demands of system-of-systems configurations and the engineering issues associated with building and supporting them.</p> <p>The "System-of-Systems Engineering for Air Force Capability Development" study was chartered to address the challenge of developing systems-of-systems that are more effective. The study panel conducted this study in response to a request by the Secretary of the Air Force and the Chief of Staff of the Air Force.</p>				
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